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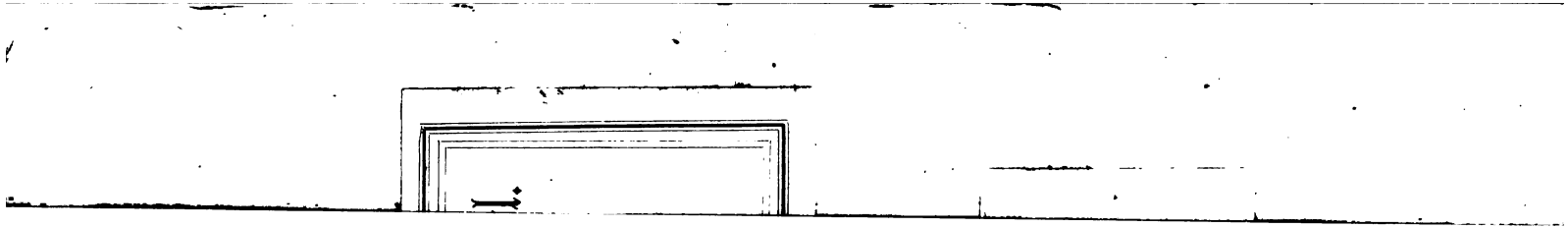

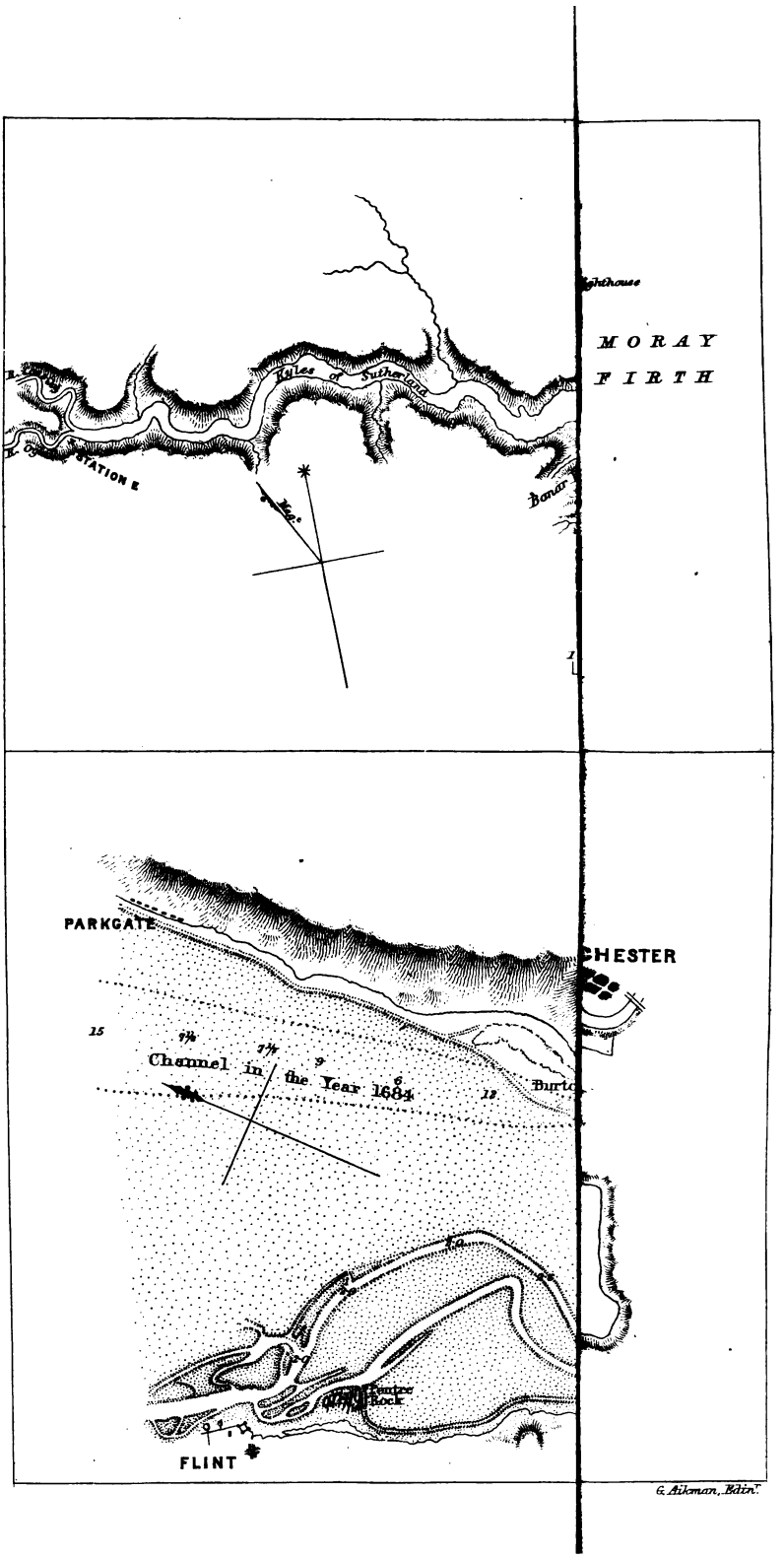
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Channel in the Year 1684
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CANAL

AND

RIVER ENGINEERING,

BEING THE ARTICLE "INLAND NAVIGATION," FROM THE EIGHTH EDITION OF THE ENCYCLOPÆDIA BRITANNICA.

BY

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PREFATORY NOTE.

THE following pages, which form the article INLAND NAVIGATION in the Eighth Edition of the *Encyclopædia Britannica*, are published as a separate Treatise at the request of the Publishers.

They were prepared at occasional short intervals of leisure from professional avocations; and in laying them in their present shape before the public, the Author thinks it necessary to remind the reader that they were originally written, not as a strictly professional treatise, but as a contribution to an Encyclopædia, the articles in which ought not only to contain the first principles of the subjects treated, and the state of our knowledge regarding them brought down to the latest period, but ought also to possess, to some extent, the character of a historical record of their rise.

This the Author has endeavoured to do with the subject of Inland Navigation. Although, there-

fore, the following pages may contain much that is not new, still, from a pretty extensive experience in designing and executing the class of works of which they treat, he entertains the hope that they may be found to embrace full information on the present state of our knowledge of a highly important branch of Hydraulic Engineering.

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INLAND NAVIGATION.

INTRODUCTION.

THE mariner's compass, it is believed, was first used at the commencement of the fourteenth century. Its introduction gave a new character to commercial enterprise, as it afforded the means of promoting to an almost unlimited degree the progress of maritime discovery. Since that early period the pursuit of Navigation has not only been the grand object to which the labours of Columbus and of all subsequent explorers of the world have been directed; but the researches of the philosopher, the astronomer, the geographer, the mechanician, and the engineer, have all been instrumental in bringing to maturity and perfection the various branches which constitute the system of Navigation as it now exists. Origin of navigation.

That system, though made up of many subsidiary parts, may conveniently and naturally be divided into two great departments. One of these is treated of in a separate article under the head of NAVIGATION;[1] the other, which forms the subject of the present treatise, is termed Inland Navigation. It may shortly be defined as that branch of navi- Its division into two departments.

[1] See Eighth Edition of *Encyclopædia Britannica*, vol. xvi.

What inland navigation is.

gation which extends from the sea to the land, and affords the means of transport throughout the interior of a country. To form a correct estimate of the importance of this subject, it must be viewed in connection with the entire system of which it forms a part. For, how can we fully enjoy the benefits of those mighty results of science and of art, by which sailing vessels of all classes are now enabled to transport their cargoes from shore to shore, with comparative ease and safety, and gigantic steamers to traverse the ocean with certainty and despatch, if we do not, in addition to exhibiting the beacon light to welcome the approach of ships to our coasts, afford the means of withdrawing them from the ocean billows into sheltered havens, where their lading may be discharged, and cargoes of our country's produce may be shipped for foreign lands. It should be borne in mind, that it is only when the mariner approaches his destined port that the dangers caused by rocks, shoals, sand-banks, tides, and currents, beset his course; and the means of securing shelter for his vessel, and of opening up a passage into the interior of the country, may be held as embraced under the extensive subject of Inland Navigation.

Harbours.

The article HARBOURS[1] fully discusses the construction of piers and breakwaters; and our present treatise will therefore be confined to Canal and River Navigation.

Topics to be discussed in present article.

Under these general heads we propose to give a brief account of canals, as applied to the purpose of transport by means of boats, and also on the larger scale, as affording to sea-borne vessels a sheltered and direct route to their destined ports. Our notice of rivers will embrace the navigation of their upper or landward streams, and also the varied means employed in opening up and rendering navigable

[1] *Encyclopædia Britannica*, vol. xi.

their seaward or tidal compartments, which will necessarily lead us to consider the conservation of estuaries and the formation of bars. Viewed even in this restricted light, it will be found that Inland Navigation forms an extensive and intricate department of hydraulic engineering.

It is proper in the outset to state, that it is not our intention to explain the nature or principles of the varied class of works which the engineer finds it necessary to adopt in carrying out such operations as those to which we have alluded. At the present time, when so much is written on all branches of engineering, such a course would be uncalled for, and would indeed extend the present treatise greatly beyond the limits to which it must necessarily be restricted. For information as to such details, we must therefore direct the reader to the different books to which we shall have to refer, as containing full information on the subjects of which they treat. Our aim is rather to present the reader with a general *résumé* of the state of our knowledge respecting the practice of engineering, as applicable to inland navigation in all its branches, and to confine such detailed remarks as we may have to offer to those parts of the subjects only which are not fully treated in works already published; and here we must express our regret, that although we have many treatises expounding the principles of engineering, nevertheless the engineers of the present day have given comparatively few accounts of the effects that have followed the application of these principles in particular cases. In drawing up the following pages, the writer has found great difficulty in obtaining authentic information on *applied* engineering; and this must be his excuse for having in some of the sections been obliged to apply, it may be thought too largely, to his own experience for illustrations of his subject.

SECTION I.

CANALS.

Canals.

It must be obvious to all, that railways, from which we have of late years derived such inestimable advantages, have now in a very great measure superseded, and certainly for the future must prevent, the general extension of canals. The great objections to relying on canals as the medium of regular and uninterrupted internal communication in this country, are the difficulty of obtaining a sufficient supply of water to prevent stoppages during dry seasons, the interruption to which they are exposed from ice during winter, and above all, in these days of express railway trains and electric telegraphs, the very limited speed at which the boats which navigate them can be propelled. Sir John Rennie, in speaking of the successful attempts made to introduce swift boats on canals, and the great improvement that was thereby effected in canal transport, says,—"All this, however, came too late; for although it would have been readily acknowledged at an earlier period, and might perhaps for a while have retarded the railway system, yet when once the latter was established, its superiority became manifest, and its progress irresistible."[1] These truly are considerations which make canals, when compared to railways as a means of transport and communication, appear so very disadvantageous, that it may at first sight be considered as uncalled for to describe, even briefly, a class of works which, in the

[1] *Transactions of Inst. of Civil Engineers*, vol. v., p. 78.

present day, may be regarded by some readers as almost entirely superseded. But although this remark may perhaps be justly considered applicable to those canals which effect a purely inland communication from town to town, it does not, in any degree, apply to that larger class of works called ship canals, which afford to sea-borne vessels an inland course, and enable them to avoid the dangers of a lengthened coasting voyage—an object of the highest importance to navigation, and one which it is obvious cannot be superseded by a railway. But, independently of this reservation on behalf of these peculiar works, it appears to us that the simple consideration of the great antiquity of navigable canals, their wide-spread introduction throughout the world, the important place which they have so long occupied in the commercial history of every country, and above all, the noble specimens which they afford of hydraulic engineering, should lead us naturally and imperatively to give some notice of their origin and subsequent progress; and this we shall do as briefly as possible, not so much from any feeling that the subject is superseded, or is unimportant, but because it will be found fully and ably treated in the works to which we shall have occasion to refer.

Their early history.

From the writings of Herodotus, Aristotle, Pliny, and other ancient historians, we learn that canals existed in Egypt before the Christian era; and there is reason to believe that, at the same early period, artificial inland navigation also existed in China. Almost nothing, however, save their existence, has been recorded with reference to these very early works; but soon after the commencement of the Christian era, canals were introduced, and gradually extended throughout Europe, particularly in Greece, Italy, Spain, Russia, Sweden, Holland, and France.[1]

[1] Fulton *On Canal Navigation*, Lond., 1796; Vallancey's *Treatise*

In speaking, however, of the earliest of these works, it is not to be supposed that they resembled the modern canals as now constructed in our own and other countries. Early as inland navigation was introduced, it was not until the invention of canal-locks, by which boats could be transferred from one level to another, that the system was rendered generally applicable and useful; and it has been truly remarked, "that to us, living in an age of steam-engines and daguerreotypes, it might appear strange that an invention so simple in itself as the canal-lock, and founded on properties of fluids little recondite, should have escaped the acuteness of Egypt, Greece, and Rome."[1] Not only, however, had the invention escaped the notice of the ancients, but what is more striking, the several gradations made towards the attainment of that simple but valuable improvement appear to have been so gradual that, like many discoveries of importance, great doubts exist as to the *person* and even the *nation*, by whom canal-locks were first introduced. One class of writers attributes the discovery to the Dutch; and Messrs Telford and Nimmo, who are understood to have written the article on Inland Navigation in *Brewster's Edinburgh Encyclopædia*, adopt the conclusion that locks were used in Holland nearly a century before their application in Italy: while, on the other hand, the invention has been strongly and not unreasonably claimed for engineers of the Italian school, and, in particular, for Leonardo da Vinci, the celebrated engineer and painter. Without, however, entering into a discussion of this question, which it is now probably impossible to solve, we may safely state, that during

on Inland Navigation, Dublin, 1763; Tatham's *Political Economy of Inland Navigation*, London, 1799; "Inland Navigation," Brewster's *Edinburgh Encyclopædia*.

[1] *Quarterly Review*, No. cxlvi., p. 281; *Treatise on Navigable Canals*, by Paul Frisi.

the fourteenth century the introduction of locks, whether of Dutch or Italian origin, gave a new character to inland navigation, and laid the basis of its rapid and successful extension. And here it may be proper to remark, that the early canals of China and Egypt, although destitute of locks, do not appear to have been on that account formed on a uniformly level line unadapted to varying heights. It is very doubtful, indeed, if the use of locks has even yet been introduced into China, intersected as it is by many canals of great antiquity and extent;[1] and in order to pass boats from one level to another, the Chinese have, from a very early period, employed stop-gates and inclined planes of rude construction. Nevertheless, the invention of locks was, as already noticed, a most important step in the history of canals; and that mode of surmounting elevations may be said to be almost universally adopted throughout Europe and America. Inclined planes and perpendicular lifts have, it is true, been employed in these countries, as will be noticed hereafter; but the instances of their application are undoubtedly rare.

Languedoc Canal.

But in proceeding to illustrate the progress of canals, we may, without tracing their gradual introduction from country to country, remark at once, that we find the French, at the end of the seventeenth century, in the reign of Louis XIV., forming the Languedoc Canal, designed by Riquet, between the Bay of Biscay and the Mediterranean, a gigantic work which was finished in 1681. It is 148 miles in length, and the summit level is 600 feet above the sea; while the works on its line embrace upwards of one hundred locks and about fifty aqueducts,—the whole forming an undertaking which is a lasting monument to the skill and enterprise of its pro-

[1] The imperial canal of China is about 1000 miles in length.

jectors; and with this work as a model, it seems strange that Britain should not, till nearly a century after its execution, have been engaged in vigorously following so laudable an example. This seems the more extraordinary, as the Romans in early times had executed works in England, which, whatever might have been their original use, whether for the purposes of navigation or drainage, were ultimately, and that even at an early period, converted into navigable canals. Of these works, we particularly specify the Caer Dyke and Foss Dyke cuts in Lincolnshire, which are by general consent admitted to have been of Roman origin. The former extends from Peterborough to the River Witham, near the city of Lincoln, a distance of about 40 miles; and the latter extends from Lincoln to the River Trent, near Torksey, a distance of 11 miles. The Caer Dyke exists now only in name; but the Foss Dyke is at this moment an efficient and flourishing navigation; and having been lately professionally engaged in its improvement, the writer had occasion to inquire somewhat minutely into its history. Regarding this *oldest* British canal, Camden, in his *Britannia*, states that the Foss Dyke was a cut originally made by the Romans, and that it was deepened in the year 1121 by Henry I.; but to what extent it was deepened does not appear. In 1762 it was reported on by Smeaton and Grundy, who found the navigable depth at that time to be 2 feet 8 inches, and recommended several works for its improvement, which appear, however, not to have been executed. In 1782 Smeaton was again employed, and deepened the navigation to 3 feet 6 inches; but it does not appear that its width was increased;[1] and from that period it remained in a very imperfect state till 1840, when Messrs

Ancient Roman canals in England.

Foss Dyke Canal.

[1] Smeaton's *Reports*, vol. i., p. 55, London, 1786.

Stevenson of Edinburgh were employed to design works for assimilating the Foss Dyke, both as regarded the breadth and depth of the navigable channel, to the Rivers Witham and Trent, with which it communicated. Upon examination, the depth of the Foss was found to be 3 feet 10 inches, and its breadth in many places was insufficient for the passage of boats, for the convenience of which occasional passing places had been provided; and it was resolved to increase its dimensions, and otherwise repair the whole work. Accordingly, the canal was widened to the *minimum* breadth of 45 feet, and deepened to the extent of 6 feet throughout; alterations which were accomplished without stopping the traffic. The entrance-lock was renewed, and a pumping-engine was erected for supplying water from the River Trent during dry seasons; and that ancient canal, which is quoted by Telford and Nimmo "as the oldest artificial canal in Britain," is now in a state of perfect efficiency, forming an important connecting link between the Trent and Witham navigations.

Bridgewater Canal.

Notwithstanding the existence of this early work, however, and of some others in the country, particularly the Sankey Brook navigation, opened in 1760, it is generally admitted that the formation of the Bridgewater Canal in Lancashire, the act for which was obtained in 1759, was the commencement of British canal navigation; and that Francis, Duke of Bridgewater, and Brindley the engineer, who were its projectors, were the first to give a practical impulse to a class of works which, under the guidance mainly of Smeaton, Watt, Jessop, Nimmo, Rennie, and Telford, has been very generally adopted throughout the country, and has undoubtedly been of vast importance in promoting its commercial prosperity.[1] It is believed that

[1] *History of Inland Navigation, particularly those of the Duke of*

the canals which have been constructed in Britain exceed in the aggregate 4713 miles, and the system has been extensively carried out both in Europe and America.

Ship canals.

The introduction of canals adapted for the passage of boats was soon followed by a larger class of works, suited for the accommodation of sea-borne vessels. Thus the Forth and Clyde Canal, projected by Smeaton in 1766, and the Crinan Canal, executed by Rennie, are examples of navigations to enable sea-borne vessels of small size to pass from opposite coasts of the country, and escape long, and it may be hazardous, sea voyages. But these works are completely surpassed by others which have been formed on a scale of much greater magnitude, to admit vessels of heavy burden and large draught of water. Of these we may mention the Great North Holland Canal, designed and constructed by M. Blanken.[1] That canal, which extends from Amsterdam to the Helder, a distance of 51 miles, was finished in 1825. It is about 125 feet in breadth at the water surface, 31 feet at the bottom, and no less than 20 feet in depth of water; and what is most worthy of notice, and is indeed a characteristic of all Dutch engineering works, the greater part of it is protected from the German Ocean by embankments faced with wicker-work, the surface of the water in the canal being below the level of the sea at high-water. At the time the writer inspected this work the sea was several feet higher than the surface of the water in the canal, and the vessels were actually being locked *down* from the ocean into the fertile plains of Holland. The object of this canal is to enable vessels trading from Amsterdam to avoid the islands and sand-

North Holland Canal.

Bridgewater, Lond., 1786; Hughes' "Memoir of Brindley," Weale's *Quarterly Papers*, London, 1843.

[1] *Transactions of Inst. of Civil Engineers*, vol. vi., p. 81.

banks of the dangerous Zuider Zee, the passage through which in former times often occupied as many weeks as the transit through the canal now occupies hours.[1]

Caledonian Canal.

But our own country furnishes us with a similar work of great magnitude and boldness; we allude to the Caledonian Canal, originally projected by Watt and Jessop, and ultimately executed by Telford, which forms an inland navigation, composed partly of natural lakes, and partly of artificial canal, extending from Inverness to Fort-William, a distance of 60 miles. The artificial part of it is 120 feet in width at the top-water level, 50 feet at the bottom, and affords 20 feet of maximum depth. By means of this inland communication vessels are enabled to avoid the dangers of the Pentland Firth, and also in some measure the intricate navigation of the Western Islands; and while the Dutch in their great canal had to encounter the difficulties occasioned by the proverbial *lowness* of their country, Telford, in constructing the Caledonian Canal, had to deal with the ruggedness of a succession of Highland glens, and to surmount the summit-level of Loch Oich, which is about 80 feet above the level of the sea. Accordingly, in addition to many heavy works which occur in its course, there is at one point on the Caledonian Canal a succession of eight locks, by means of which a vessel of nearly the largest class of merchantmen can be raised or lowered through a height of 60 perpendicular feet. The locks, which are in close succession, rise one above another like a series of gigantic steps; and this unique and extensive marine ladder has not inappropriately been termed "Neptune's Staircase."[2]

[1] It was here that Bakker, a burgomaster of Amsterdam in 1688, introduced his "camel" for floating large vessels over the shoals of the Pampus, by means of which, according to Sir John Leslie, an Indiaman which drew 15 feet water had its draught reduced to 11 feet.

[2] The connection of the Atlantic and Pacific oceans by means of

Difficulties in constructing canals.

It must be obvious that, in successfully carrying out works of such a nature, and on so gigantic a scale, no ordinary amount of engineering skill is requisite. Vast reservoirs must in some cases be formed for storing the water necessary to supply during dry seasons the loss by lockage, leakage, and evaporation. Feeders must be made to lead this water to the canal; hills must be pierced by tunnels; valleys must be crossed on lofty embankments, or spanned by spacious aqueducts; and above all, the whole must be conceived and laid out with scrupulous regard to the all-important object of securing the works against injury from an overflow of water during floods, and a consequent inundation of the surrounding country. Moreover, the necessity of laying out the canal in level stretches, and surmounting elevations by means of locks or inclined planes, occurring at intervals, often occasions much difficulty, and greatly restricts the resources of the engineer. Taking, then, all these circumstances into consideration, and bearing in mind that canals were the pioneers of railways, we think it may safely be affirmed that the canal engineers of former days had much more serious *physical* difficulties to contend with than are experienced in carrying out the railways in modern times; if we except such works as the Britannia Bridge, the high-level bridge of Newcastle, the Boxhill Tunnel, and some other kindred works. But, indeed, their *mechanical* difficulties were also greater; for the introduction of steam, and its wide-spread application to all engineering operations, affords facilities to the

a navigable canal has long been under consideration, and the question has of late years assumed a more practical aspect. (For a review of the various schemes which have been proposed for carrying out this desirable object, the reader is referred to communications by Mr Joseph Glynn and Lieut.-Col. Lloyd, in the *Transactions of the Society of Civil Engineers*, vol. ix., p. 58, and vol. vi., p. 399.)

engineers of modern times which Smeaton at the Eddystone, Stevenson at the Bell Rock, and Rennie and Telford in their early navigation works, did not enjoy. We therefore gladly embrace this opportunity of acknowledging the distinguished merits of the engineers who practised at the end of the former and the commencement of the present century.

General principles of canal construction.

We have already said that we cannot in this treatise enter into details as to the construction of the various works adopted in executing canal navigations; and we shall here close our short historical notice of these works by submitting the following digest of the general principles which should guide the engineer in selecting the route and designing the construction of a line of canal:—

Supply of water.

1. The first object to which attention ought to be directed is the supply of water, on which the efficiency of a canal mainly depends. If there be no natural lake in the district available for storage, the engineer must select such situations as are suitable for the construction of artificial reservoirs. The conditions to be attended to in selecting the positions for these works are, that they command a sufficient area of drainage to supply the necessary amount of water; that their offlets are at such an elevation as to admit of water being conveyed to the summit-level of the canal; and that the embankments for retaining the water be erected on sites affording a favourable foundation, and so situated with reference to the valley above them that they shall, with the minimum height and breadth of embankment, dam up the maximum amount of water. It is further necessary to consider whether the subsoil of the valley forming the reservoirs is throughout of so retentive a nature as to prevent leakage; and it is also essential to provide, by means of waste weirs, for the discharge of floods. The Caledonian Canal

is, in this respect, very favourably situated; no artificial reservoir having been required. Nearly the whole supply is derived from Lochs Ness, Oich, and Lochy, which, indeed, constitute the greater part of the navigation; they afford ample depth of water, and though on different levels, they extend in an almost continuous line through the country. In other cases, such as the Union, Forth and Clyde, Crinan, Birmingham, and other canals, it has been found necessary to construct large artificial reservoirs, from which the water is led in feeders to points convenient for forming a junction with the canal. The water in these reservoirs, whether artificial or natural, is stored up in winter, and let off as required during the droughts of summer. In situations where the canal communicates with the sea or a tidal river, and where the natural supply is small, as in the case of the Foss Dyke, the water may be raised by pumping-engines.

Reaches and locks.

2. In determining the direction of a canal, it is of importance to consider the levels of the country through which it passes, and to lay out the work in a succession of level reaches, so as to overcome elevations *in cumulo* at those places where it can be most advantageously effected. This arrangement not only leads to a saving of attendance and expense in working the canal, but is also more convenient as presenting fewer stoppages to the traffic. The means of overcoming the difference of level between the various reaches must depend very much on circumstances. With few exceptions, the change of level is effected by means of locks, which generally have a lift of from 8 to 10 feet, though in some cases it is somewhat greater. The dimensions of the locks ought to be regulated by the traffic; but they should, in order to save water, be as near as possible the size of the craft to be

passed through them. The smallest class of canals have locks about 8 feet in breadth, and from 70 to 80 feet long; those on the Forth and Clyde are 20 feet in breadth, and 74 feet long; on the Caledonian Canal they are 40 feet broad, and 180 feet long, and on the great Holland ship-canal they are 51 feet broad, and 297 feet long. The water is gradually admitted into and flows from each lock by sluices formed in the gates. Sir William Cubitt, in carrying out the improvements of the Severn navigation, introduced the water through a culvert parallel to the side wall of the lock, and opening in the centre by means of a tunnel, which admits 16,000 cubic feet of water to flow into or out of the lock in 1½ minute; and in little more than that time loaded vessels can be passed through.[1] Inclined planes and perpendicular lifts, which have the great advantage of saving water, have also been adopted in a few cases. In 1837 the writer inspected the Morris Canal in the United States, constructed by Mr Douglas of New York, on the line of which there are no fewer than 23 inclined planes, having gradients of about 1 in 10, and an average lift of 58 feet each. The boats weighed, when loaded, 50 tons, and after being grounded on a carriage, were raised by water-power up the inclines with great ease and expedition. The length of the Morris Canal, which connects the Rivers Hudson and Delaware, and is a most interesting work, is 101 miles, and the whole rise and fall is 1557 feet, of which 223 are overcome by locks, and the remaining 1334 by inclined planes.[2] But inclined planes were used on the Ketling Canal in Shropshire in 1789, and afterwards on the Duke of Bridgewater's Canal. Mr Green introduced on the Great Western Canal a perpendicular lift of 46 feet; and

[1] *Transactions of Institution of Civil Engineers.*
[2] Stevenson's *Sketch of Civil Engineering in North America.*

more recently Mr Leslie, of Edinburgh, and Mr Bateman, constructed an inclined plane on the Monkland Canal, wrought by two high-pressure steam-engines of 25 horse-power each. The height from surface to surface is 96 feet, and the gradient is 1 in 10. The boats are not wholly grounded on the carriage, but are transported in a caisson of boiler-plate, containing 2 feet of water. The maximum weight raised is from 70 to 80 tons, and the whole transit is accomplished in about 10 minutes. For the five years previous to the end of 1856, the average number of boats that passed over the incline each year was 7500. Sir William Cubitt has also introduced three inclined planes, having gradients of 1 in 8, on the Chard Canal, Somersetshire. One of these inclines overcomes a rise of 86 feet; and they are said to act very satisfactorily.[1]

Waste weirs.

3. An essential adjunct to a canal is a sufficient number of waste weirs to admit of the discharge of the surplus water which accumulates during floods, and which may, if not provided with an exit, rise to such a height as to overflow the tow-path, and cause a breach in the banks, producing stoppage of the traffic and damage to the adjoining lands. In determining the number and positions of these waste weirs, the engineer must be guided entirely by the nature of the country through which the canal passes. Whenever an opportunity occurs of discharging surplus water into a stream crossed by the canal, a waste weir may safely be introduced; but, independently of this natural facility, the engineer must consider from what quarters, and at what points, the greatest influx of water may be apprehended, and must at such places not only form waste weirs of sufficient size to void the surplus, but prepare artificial courses for their discharge into the nearest streams. These

[1] *Transactions of Institution of Civil Engineers*, vol. xiii., p. 205.

waste weirs are overflows placed at the top water-level of the canal, so that in the event of a flood occurring, the water flows over them, and thus relieves the banks. The want of sufficient escape for flood-water has occasioned overflows of canal banks which were attended with very serious injury to the works, and lengthened suspension of the traffic; and attention to this particular part of canal construction is of essential importance.

Stop-gates.

4. Another very necessary precaution is the introduction of stop-gates at short intervals of a few miles, for the purpose of dividing the canal into isolated reaches, so that in the event of a breach occurring, the stop-gates may be shut, and the discharge of water confined to the small reach intercepted between them, instead of extending throughout the whole line of canal. In large works these stop-gates may be most advantageously formed in the same manner as the upper gates of locks, two pairs of gates being made to shut in opposite directions. In small works they may be made of thick planks, which are slipped into grooves formed at those narrow parts of the canal which occur under road bridges, or at contractions made with grooves at intermediate points to receive them. Self-acting stop-gates have been tried, but their success has not been such as to lead to their general introduction. Stop-gates are further found to be very useful in cases of repairs, as they admit of the water being run off from a short reach, when the repairs can be made, and the water restored, with comparatively little interruption to the traffic. Their value in obviating serious accidents was well exemplified on one occasion in the experience of the writer, when the water during a heavy flood flowed over the towing-path at the end of an aqueduct adjoining a high embankment, and the uncontrolled current carried away the embankment, and the

soil on which it rested, to the depth of 80 feet, as measured from the top water-level. The stop-gates were, on the occasion referred to, promptly applied, and the discharge confined to a short reach of a few miles, otherwise the injury (which was, even in its modified form, very considerable) would have been enormous.

5. For the purpose of draining off the water to admit of repairs after the stop-gates have been closed, it is necessary to introduce, at convenient situations, a series of exits called offlets, consisting of pipes placed at the level of the bottom of the canal, and fitted with sluices which can be opened and shut when required. These offlets are generally formed at aqueducts or bridges crossing rivers where the contents of the canal can be run off directly into the bed of the stream, the stop-gates on either side being closed so as to isolate the part of the canal from which the water is withdrawn.

Drainage of tow-paths.

6. In executing the work, provision must be made for the proper drainage of the tow-paths, especially in cuttings. The drainage of the tow-paths should be carried to a sky drain at the bottom of the cutting, and at intervals passed below the tow-path into the canal. The preservation of the banks at the water-line is also a matter of importance. "Pitching" with stones and "facing" with brushwood are employed, and, in the writer's experience, the latter, if well executed, forms an economical and effectual protection.

Puddling.

7. In forming the *alveus* or bed of the canal, care must be taken, particularly on embankments, and also in cuttings, if the soil is porous, to provide against leakage by the application of puddle. And here it is proper to remark, that an all-important matter, as affecting the construction of the works, is the possibility of getting clay in the district, or such other soil as may be worked into puddle,

on the good quality of which the stability of the reservoir embankments, and the imperviousness of the beds and banks of the canal, mainly depend.

These are the only points of general application in the construction of canals to which we can advantageously direct attention in the present communication. In carrying them into practice, the engineer must be guided partly by the valuable details to be found in the works to which reference is made in this article, but mainly by that experience which can be gained only by the study of works in actual operation.

We do not propose to extend our remarks to the means of conducting traffic on canals and rivers, and have to refer the reader for information on that subject to observations and works on Traction and Steam Navigation. On the former subject the reader may consult the observations, by Mr Walker and Mr George Rennie, in the *Transactions of the Royal Society* and of the *Institution of Civil Engineers*; and especially the very valuable researches on Hydrodynamics, by Mr Scott Russell, in the *Edinburgh Philosophical Transactions*. On the latter he is referred to the articles STEAM-ENGINE, and STEAM NAVIGATION,[1] in the *Encyclopædia Britannica*.

[1] Researches on Hydrodynamics, from *Trans. of Royal Society of Edinburgh*, 1837, by J. S. Russell; "On the Resistance of Fluids to Bodies passing through them" (*Philosophical Transactions*, 1828), by James Walker, C.E.

SECTION II.

RIVERS, THEIR PHYSICAL CHARACTERISTICS.

Difference between canal and river navigation.

From what has been said, it will be seen that a canal may be described as a work by which water is diverted from its natural course, and made to occupy a channel prepared for its reception, extending through the country for the transport of boats and vessels. Canal navigation is thus entirely *artificial* in its character. In this respect it differs from river navigation, which may be described as the art of using, for the purposes of inland communication, rivers flowing in their natural courses, and of applying means to render them subservient to the purposes of navigation in cases where the depth is limited, or where rapid currents exist. Our consideration of rivers must therefore necessarily comprehend a general sketch of their physical characteristics, and the laws of their motion, as a necessary introduction to the more practical part of the subject, embracing the engineering works required for their improvement, with which we have chiefly to deal in this treatise.

The compartments described as occurring in rivers.

As introductory, therefore, to the remarks which are to follow, it seems desirable to premise, as described by the writer in a communication to the Royal Society of Edinburgh,[1] that in all rivers affected by tidal influence, two physical boundaries, more or less apparent, are invariably found to exist, caused by the influx of the tidal wave through firths or bays, and the modification it receives in its passage up the

[1] *Proceedings of the Royal Society of Edinburgh*, vol. ii., p. 26.

gradually rising inclination or slope of a river's bed. These boundaries again produce three compartments. The seaward, or lowest of these, the writer termed the "sea proper;" the next, or intermediate one, into which the sea ascends, and from which it again withdraws itself, was termed the "tidal compartment of the river;" and the highest, or that which is above the influence of the sea, the "river proper." Their relative extent in different situations is influenced not only by the circumstances under which the great tidal wave of the ocean enters the river, but by the size of its stream, the configuration and the slope of its bed, and, in short, by every natural or artificial obstruction which is presented to the free flow of the tidal currents along its channel.

Their physical characteristics.

These three compartments possess very different physical characteristics. The presence of *unimpaired tidal phenomena* in the lowest, the *modified flow of the tide*, produced by the inclination of the river's bed in the intermediate, and the *absence of all tidal influence* in the highest compartment, may be shortly stated as the phenomena by which these spaces are to be recognised. The tides in the "sea proper" compartment of an estuary, for example (although the place of observation be several miles embayed from what in strictness could be called the "sea" or "ocean"), will be found to resemble those of the adjoining sea with which it communicates,—1*st*, in the identity of the levels of low water; 2*d*, in the shortness of the time which elapses between the cessation of ebbing and the commencement of flowing, or, in other words, the absence of any protracted period of low water, during which the surface appears to remain stationary at the same level; 3*d*, in the symmetrical form traced by the passage of the tidal wave; and 4*th*, in the range of tide, so far as that is not influenced by the formation of the shores in narrow seas or channels. In

ascending into the intermediate compartment, however, the level of the low water is no longer the same; the range of tide, excepting in peculiar cases, becomes less, and is gradually decreased as the bed of the river rises, and at length a point is reached where its influence is not perceptible. In this intermediate section the phenomena of *ebbing* and *flowing* are still found to take place, but the times of ebb and flow do not remain constant, that of ebb gradually gaining the ascendency; the duration of low water being gradually protracted as we proceed upwards, until the influence of tide is unknown. This forms the boundary line of the upper compartment, the characteristic of which is the total absence of ebbing and flowing; the river at all times pursuing its downward course in an uninterrupted stream, and at an unvarying level, except in so far as may result from the changes due to land floods.

In the investigation of these different characteristics, the variable nature of the elements to be dealt with must be kept in view. The river, for example, is liable to be affected by floods, and the state of the tides by winds and other causes; and therefore a great degree of precision in defining these spaces cannot in all cases be expected, nor indeed is it necessary for the purpose of the present inquiry. But it is satisfactory to know that the termination of the low-water level at the separation of the seaward and intermediate spaces, as laid down by marine surveyors, simply from observation of the tidal phenomena, has in several situations been found to agree exactly with the position of that boundary as determined by engineers by means of accurate levelling, combined with careful tidal observations.

But an example in actual practice will best illustrate what is meant, and for this purpose we shall refer to the

investigation of the tidal phenomena, made by the writer in 1842, of the Firth of Dornoch and Kyles of Sutherland in Cromartyshire. By referring to the small chart of the Dornoch Firth in Plate I., the reader will be better able to follow the illustrations to be given. The harbour of Portmahomac, marked A on the chart, about 3 miles from Tarbetness Lighthouse, was selected as the place at which to observe the *ocean* or *sea wave*. The second station at which it was found convenient to institute observations was within the Firth at Meikleferry, marked B, about 3 miles above the town of Tain, and 11 miles distant from Portmahomac. The third station was at Bonar Quarry, marked C, situated on the north shore of the Firth, and 8 miles inland from Meikleferry; and the fourth station was at Bonar Bridge, marked D, one mile from the Bonar Quarry. Beyond Bonar Bridge the observations were also extended as far as the junction of the Rivers Oykell and Cassley, marked E, a distance of 12½ miles; so that the whole distance embraced in the investigation was 33½ miles. Graduated tide-gauges were fixed at Portmahomac, Meikleferry, Bonar Quarry, and Bonar Bridge; and by means of two distinct sets of observations, the levels of these gauges, in relation to each other, were accurately determined, so that all the tidal observations made at them could be reduced to the same *datum* line. The result of the observations was, that *the low-water of each tide is, practically speaking, on the same level at Portmahomac, Meikleferry, and Bonar Quarry*. We use the word *practically*, because the level of the sea is more or less affected by every breeze of wind, which necessarily must *pen up* and elevate some portions of its surface, and cause corresponding depression, at other places, so that an unvarying low-water line will not be found to exist throughout a series of tides on any part even of the

Tidal phenomena of Dornoch Firth.

Low water line practically level from Portmahomac to Bonar Quarry.

ocean itself, however limited the number of low-waters embraced may be. Accordingly, deviations from a truly level line of a few inches occasionally occurred in the observations made at the Dornoch Firth; but these were not of greater extent than could reasonably be traced to the effect of wind, and were found to vary, not only in their amount, but also in their value, being sometimes *plus* and sometimes *minus* quantities, causing corresponding variations in the results deduced from the different series of tidal observations that were made. Some of these showed the low-water within a fraction of an inch of being level; while others gave a notable *elevation* at some of the stations; and others, again, gave a *depression* below the level line at the very stations where previously there had been a rise.

To illustrate this more fully, we shall give a few examples: Thus, on the 23d of June (on which day the weather happened to be very calm), the level of low-water at Meikleferry was three-quarters of an inch *above* that at Portmahomac; and on the next day, the wind blowing fresh from the S.E., the level of low-water at Meikleferry was $3\frac{3}{4}$ inches *above* that at Portmahomac. Again, a succeeding observation gave the level of Meikleferry three-quarters of an inch *below* Portmahomac. In the same way, and in similar small degrees, the level between the low-water at Bonar Quarry tide-gauge and at Portmahomac was found to vary. The *average* of all the observations made, gave the level of low-water at Meikleferry 2·2 inches *above* that at Portmahomac, and the level of low-water at Bonar Quarry 1·1 inch *below* the low-water at Portmahomac. Whether these *average* differences of level be traceable to the effects of prevailing winds, which may be supposed to have exerted a greater influence on the water at the more exposed stations, or to

any inaccuracy in the levels, must evidently, from the examples given of the extent and nature of the daily deviations, be a point which we cannot determine; but the result of a lengthened train of observations, notwithstanding the *average* difference above stated, may fairly be held to be, that the low-water of each tide is *practically* on the same level at Portmahomac, Meikleferry, and Bonar Quarry; and therefore that the *low-water* tidal phenomena, throughout the whole extent of the firth, correspond with those of the sea.

Low-water rises from Quarry to Bonar Bridge.

But when the results of the observations at Bonar Bridge come to be compared with those made at the seaward station, a very marked difference presents itself; for, while the low-water line is found to be practically level from Portmahomac to Bonar Quarry, a distance of 20 miles, throughout a narrow firth, varying from 1¼ mile to 550 feet in breadth at low-water, we find that between the Quarry and Bonar Bridge, a distance of only one mile, there is a rise in the low-water line of spring-tides of no less than 6 feet 6 inches. It was therefore concluded that, in the Dornoch Firth, the point at which the low-water level of spring-tides met the descending current of fresh water, lay somewhere between the Quarry and Bonar Bridge. A different series of observations was made to ascertain the exact point at which this junction takes place, and the result of these observations was, that at low-water of an ordinary spring-tide, rising 14 feet at Meikleferry, the low-water level of the sea meets or intersects the descending fresh-water stream from the Kyle of Sutherland, at a point 1700 yards below Bonar Bridge, or nearly opposite Kincardine Church, and within 60 yards of the Quarry station. Between this point and the bridge, a distance of 1700 yards, there is a rise of 6 feet 6 inches, giving an average slope on the bed of the river of 1 in 784, or 6·7 feet per mile.

In addition to this uniformity in the level of low-water, it was further found that the tidal phenomena of the firth corresponded to that of the adjoining sea, in the outline traced by the passage of the tidal wave, as deduced from observations made at the different stations on the rise and fall of the tide-level between the periods of low and high water. During the period between each low-water or high-water the level of the surface was ever varying, there being no lengthened cessation of ebbing and flowing, the tide-wave being fully developed at the whole of the stations up to Bonar Quarry. The range of tide was indeed increased in the inner part of the firth to the extent of 9 inches at Meikleferry, and 12 inches at Bonar Quarry; that is, when the rise of tide was 12 feet 8 inches at Portmahomac, it was 13 feet 5 inches at Meikleferry, and 13 feet 8 inches at Bonar Quarry—an increase which is due to the momentum of the tidal wave when obstructed by the contracting shores of the firth, and is accounted for by the principle of the conservation of forces.[1]

Rise of tide at Bonar Bridge.

But if we inquire into the tides at Bonar Bridge, we find that they do not correspond with those of the adjoining sea or of the firth; for taking the tide to which we have already alluded, which rose 13 feet 8 inches at Bonar Quarry, it was found on the same day to rise only one-half of that amount, or 6 feet 10 inches at Bonar Bridge; the difference between the two results being occasioned by the rise on the low-water line of the channel between these two places. The tide on the particular day alluded to rose no less than 6 feet 10 inches at Bonar Quarry before it attained the level of the low-water at Bonar Bridge, when it began to rise at that place also, and afterwards continued to flow nearly uniformly at

[1] Essay towards a First Approximation to a Map of Co-tidal Lines, by the Rev. W. Whewell, *Philosophical Transactions*, 1833.

both places. Fig. 1 is a diagram illustrative of the form of the tide-wave at Meikleferry and Bonar Bridge, the hard

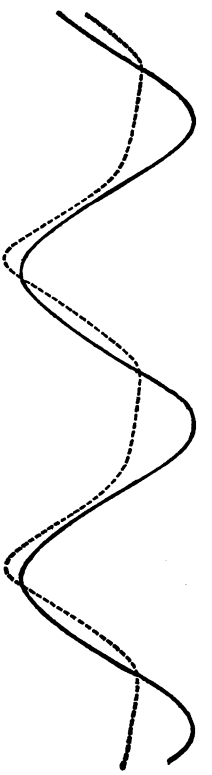


Fig. 1.
Form of tide-wave.

line represents the curve formed by the passage of the tidal wave at Meikleferry, and the dotted line shows that at Bonar Bridge. In both cases the vertical space represents the

rise of tide, and the horizontal space the elapsed time. From this diagram it will be seen, that while the tide at Meikleferry is symmetrical, and presents a constantly rising or falling outline, the tide at Bonar Bridge represents a long period, extending on some occasions by actual observation to several hours at low-water, nearly unaffected by tidal influence, during which period the water stood almost at the same level. The tidal water admitted into the upper part of the estuary above Bonar Bridge took a considerable time to drain off through the narrow water-way at that place, and hence the water did not attain a permanent low-water level, even long after the tide had ceased to operate in affecting its surface. The observations made to ascertain how far the tidal influence extended up the Kyles of Sutherland were conducted with the same care, and proved that the highest point influenced by the tide was at the junction of the Rivers Oykell and Cassley, 12½ miles above Bonar Bridge.

Mean sea-level.

A further test of the "sea proper" will, it is believed, be found in the existence, at any place of observation within that compartment, of a central point in the vertical range of tide from which the high and low water levels of every tide are very nearly equidistant. The existence of such a point was, it is believed, first determined by Mr James Jardine at the Tay in 1810,[1] and has been observed in the firths of Forth and Dornoch, at the Skerryvore Rocks on the west of Scotland, at the Isle of Man, and in the Mersey. These different series of observations, made at points so far distant from each other, seem to prove the universality of the phenomenon, at least on the shores of this country. But in ascending into the tidal compart-

[1] *Report* by James Jardine, C.E.

ment, the rise on the low-water level, which has already been described, destroys at once the symmetry of the tide-wave, as shown in fig. 1, and the existence of any such central point equidistant from the high and low water level of each tide.

The case we have adduced will serve to illustrate the definition we have given of the compartments of rivers. From Portmahomac to Kincardine, near Bonar Quarry, we have all the evidences of what we have termed the "sea proper;" the line traced through the low-water mark at different parts of the firth is practically level; the curve formed by the rise and fall of the tide is symmetrical; there is no lengthened cessation of ebbing and flowing at the period of low water; and the range of tide is unmodified save by the additional rise due to the narrow frith through which the tide-wave passes. From Kincardine to the junction of the Oykell and Cassley, we have proofs no less evident of the modified flow of the tide peculiar to the "tidal compartment." Even at Bonar Bridge, one mile above the quarry, the low-water level is 6 feet 6 inches higher than at the station below. At low-water the tide remains within a few inches of the same level for several hours, and its maximum range is reduced to about one-half of what it is further seaward, while at the junction of the Oykell and Cassley it disappears altogether. Above this point no tide is known to affect the flow of the stream, which, being free from all tidal influence, may be termed the "river proper."

These boundaries not equally distinct in all cases.

We must here warn the reader not to suppose that the boundaries we have traced as existing in the Dornoch Firth, and many other places which the writer has investigated, may be determined with the same precision under all circumstances and in every case. The observations to which

we have alluded, are supposed to be made at periods when the river is free from floods and the sea unaffected by heavy gales; moreover, the configuration of the bottom and shores of a river and estuary may, in certain cases, render the accurate determination of the boundaries very difficult. All that we assert is, that these compartments do in some measure, more or less defined, exist in all cases; and although not determined with the same careful precision as explained in the case of the Dornoch Firth, we have made observations of a more general character, and with complete success, to define approximately the tidal compartments in many estuaries and rivers in Britain and Ireland.

Data required by the engineer.

But there are other data with which the engineer must be furnished before he can advantageously consider the improvement of any part of a river. These data include the determination of its slope, velocity, and discharge, the nature of its bed and banks, and many other particulars. For full details as to the character and extent of such information, and the means of obtaining it, we can only refer the reader to works on the subject of River and Marine Surveying.[1] Neither do we include in the present treatise any sketch or digest, however brief, of the interesting and gradual progress made by philosophers and engineers of the early Italian and French schools, in the theoretical and experimental investigations of the laws which regulate the flow of water in natural and artificial channels, which investigations form the basis of all our practice in hydraulic engineering. These lengthened and laborious experimental researches will be found to be most fully discussed—historically, theoretically, and practically—in the

[1] *Treatise on the Application of Marine Surveying and Hydrometry to the Practice of Civil Engineering*, by David Stevenson, C.E. Edinburgh, 1842.

valuable article by Dr Robison on the Theory of Rivers, in the *Encyclopædia Britannica*, art. RIVER, and also in the report made by Mr George Rennie to the British Association on the progress and present state of our knowledge of hydraulics as a branch of engineering.[1]

While we do not therefore propose to advert at length either to the theoretical or practical details of the subject, still the whole of river engineering is so connected with, and dependent on, those physical characteristics of rivers which are termed the *slope*, the *hydraulic mean depth*, the *velocity*, and the *discharge*, that it seems to be indispensable to a proper understanding of the subject that these elements should be defined, and that the relations which subsist between them should be considered. The following definitions will suffice to answer the purpose in view :—

Definitions.

1. The *slope* is the fall on the surface of the river, which is generally expressed in feet or inches per mile.

2. The *hydraulic mean depth* is the quotient arising from dividing the sectional area of the channel in square feet by the wetted border or perimeter in lineal feet.

3. The *mean velocity* is that velocity which is common to the whole cross section of a stream, and is represented by the discharge divided by the area of that section.

4. The *discharge* is the quantity of water yielded by the stream in a given time, and is generally stated in cubic feet.

Method of ascertaining discharge by measurement.

In the practice of engineering it is frequently necessary to consider questions involving the relations which subsist between these different elements, and many formulæ have been proposed to facilitate this operation. The Chevalier Dubuat was the first investigator who, by discovering the effects of the friction of fluids on their own particles, and

[1] *Report of the British Association for the Advancement of Science* for 1834.

on the bed along which they move, was enabled to apply his theoretical knowledge of hydraulics to practical purposes, and his views and formulæ will be found fully discussed in the article RIVER already alluded to. The writer of this article has, however, found that such formulæ are not *generally* applicable, and it seems desirable to lay before the practical engineer the various results given by different formulæ when applied under the same circumstances, in order that he may be cautioned as to relying on such a means of computation in cases where great exactness is requisite. In order to ascertain the discharge of a stream or river, the writer has therefore in practice resorted to actual measurement. For this purpose, a situation was selected where the bed was tolerably uniform in its longitudinal and transverse outline. A correct transverse section of the bed or channel was made, and the section was divided into compartments. The surface velocity in the centre of each compartment was then taken by means of floats, or the instrument called the *tachometer*. These surface velocities were reduced to mean velocities for each compartment by Dubuat's formula :—

$$M = \frac{(\sqrt{V} - 1)^2 + V}{2}$$

or more simply, in cases where great accuracy is not required,

$$M = 0{\cdot}8\ V$$

where V = the observed surface velocity in inches per second.

M = the mean velocity in inches per second.

We have found by means of the tachometer, used at different depths, that this formula expresses accurately the mean velocity of *any vertical section* of the stream to which

the observed surface velocity is applicable. But as the surface velocity on the same cross section is not uniform throughout the width of the stream, it becomes necessary, as already stated, to divide the section into compartments, so as to embrace the maximum and minimum speeds. The areas of the different sections being then multiplied by the corresponding mean velocities obtained by either of the above formulæ, the sum of the discharge due to the different compartments is held to give the total discharge of the stream or river. It is obvious that the accuracy of the result obtained by this process depends on the judgment with which the cross-sectional area is subdivided, and on the care with which the observations are made. The operation is, in many cases, attended with difficulties, and in all with a considerable consumption of time; and many formulæ have been proposed to shorten it. The writer has compared the computed discharge given by several of these formulæ with the discharge as ascertained by careful observations made in the manner described, and the following result is submitted for the information of engineers.

The formulæ subjected to trial were:—

I. Formula given by Dr Robison, founded on Dubuat's investigations:[1] Method of ascertaining discharge by formulæ.

$$M = \frac{307\,(\sqrt{d} - 0{\cdot}1)}{\sqrt{S} - \text{Hyp. log. of } \sqrt{S} + 1{\cdot}6} - 0{\cdot}3 \quad (\sqrt{d} - 0{\cdot}1)$$

in which M = the mean velocity in inches per second,
d = the hydraulic mean depth in inches,
S = the reciprocal of the slope of the surface which is the denominator of the fraction expressing the slope, the numerator being

[1] See article RIVER, *Encyclopædia Britannica*; also *A System of Mechanical Philosophy*, by John Robison, vol. ii., p. 453.

always unity (a slope of 1 foot a mile is $\frac{1}{5280}$, therefore 5280 = reciprocal for that slope),

Hyp. log. = the common log. of the number to which it is attached, multiplied by 2·3026.

II. Formula given by Sir John Leslie:[1]

$$M = \frac{15}{16}\sqrt{af}$$

in which M = the mean velocity in miles per hour,
a = the hydraulic mean depth in feet,
f = the fall on the surface in feet per mile.

III. Formula given by Mr Ellet for calculating discharge of the Mississippi:[2]

$$V = \frac{8}{10}\sqrt{df} + \frac{df}{20}$$

$$M = 0{\cdot}8\ V$$

in which V = the surface velocity in feet per second,
d = the maximum depth of the river in feet,
f = the fall on the surface in feet per mile,
M = the mean velocity in feet per second.

IV. Formula given in Mr Beardmore's tables:[3]

$$M = \sqrt{a}\ 2f \times 55$$

in which M = mean velocity in feet per mile,
a = hydraulic mean depth in feet,
f = fall per mile in feet.

V. In addition to these formulæ, the writer also subjected to trial the formula:

$$M = \frac{(\sqrt{V} - 1)^2 + V}{2}$$

[1] *Elements of Natural Philosophy*, by Professor Leslie, Edinburgh, 1829, vol. i., p. 423.

[2] *The Mississippi and Ohio Rivers*, by Charles Ellet, Philadelphia, 1853.

[3] *Hydraulic Tables*, by Nathaniel Beardmore, C.E., London, 1852.

in which M = the mean velocity in inches per second,
V = the maximum surface velocity in the axis of the stream in inches per second.

In order to compare these different formulæ, a very favourable situation was selected for ascertaining the discharge of a stream by careful measurements of its sectional area and of the velocities at different parts of its surface from the centre to either side, and the result gave a discharge of 1653 cubic feet per minute, which, from various measurements, the writer believes to be a very near approximation to the actual discharge. The slope was also accurately ascertained, and the following are the results:—

	Cubic feet.	
Discharge from measurement as above,	1653	per minute.
1*st*. By Robison's formula.....	2214	do.
2*d*. By Leslie's do.....	2474	do.
3*d*. By Ellet's do.....	2784	do.
4*th*. By Beardmore's do.....	2335	do.
5*th*. By formula assuming the mean deduced from the centre surface velocity as the mean for the whole section ...	1950	do.

It will be seen from this statement, that none of the formulæ afford a near approximation to the discharge of the small stream to which they were applied.

Again, it was ascertained by the late Dr Anderson, after most carefully dividing the cross section into compartments, that the discharge of the main branch of the Tay at Perth was 147,391 cubic feet per minute.[1] The writer has also ascertained the discharges, as calculated by the different formulæ as above, and the following are the results:—

	Cubic feet.	
Discharge per measurement	147,391	per minute.

[1] This does not include the Willowgate nor the Earn.

		Cubic feet	
1*st* by	Robison's formula	153,632	per minute.
2*d* „	Leslie's	166,134	do.
3*d* „	Ellet's	122,002	do.
4*th* „	Formula in Beardmore's tables	156,569	do.
5*th* „	Formula assuming the mean deduced from the centre surface velocity as the mean for the whole section	179,237	do.

Formula generally applicable, but affording only an approximation.

The result of these trials, and others which the writer has had occasion to make, is, that none of the formulæ that have been proposed will be found *generally* applicable. As it is often convenient, however, to be able to approximate to the velocity or discharge due to a given area and fall, the following formula may be applied, and will, in most cases, give a pretty near approximative result, viz.:—

$$x = y\sqrt{af}$$

$$z = \frac{x \times 5280}{60}$$

$$D = sz$$

in which x = the mean velocity of the whole section of the stream in miles per hour,

y = a quotient which is found to vary from 0·65 for small streams under 2000 cubic feet per minute, to 0·9 for large rivers, such as the Clyde or the Tay,

a = the hydraulic mean depth in feet,

f = the fall on the surface in feet per mile,

z = the mean velocity of the whole section of the stream in feet per minute,

s = the sectional area of the stream in feet; and

D = the discharge in cubic feet per minute.

It must still be kept in view that the application of any known formula to the determination of the mean velocity and discharge of a river is shown, by experimental inquiry, to

afford only a rough approximation; and that if a near approximation is required, it must be obtained by means of observations embracing the velocities at different parts of the cross-sectional area, made in the manner already described.

Result of formula destroyed where under-currents exist.

We must offer the further caution, that those rules whereby the mean velocity is deduced from, or is assumed as bearing any constant ratio to, the surface velocity, do not apply in many situations which are within the influence of the tide. As will be explained more fully hereafter, the fresh water of the river being specifically lighter, is to a certain extent borne up by and floats upon the denser water of the sea. In surveying the Dee at Aberdeen in 1810, Mr Robert Stevenson found that, while there was an *outward* upper-current of fresh water, there was an *inward* under-current of salt water; so that, although the upper stratum was constantly running toward the sea, there was a regular rise and fall of the surface produced by the influx of the tidal waters below. Another instance of such an under-current, though not occasioned by the presence of a river, was found to exist in a marked degree at the Cromarty Firth by Mr Alan Stevenson in 1837. The waters of the Cromarty Firth pass to and from the sea through the narrow gorge between the Suters of Cromarty, where the width is about 4500 feet, and the depth about 150 feet. The mean velocity due to the column of water passing this gorge, as deduced from the observed surface velocity, was not sufficient to account for the quantity of water actually passed during each tide, as determined by measuring the cubical capacity of the basin of the firth. This led to the observation of the under-currents through the gorge by means of submerged floats, and it was found that during flood-tides the surface velocity was 1·8 mile per hour; while at the depth of 50 feet the velocity was not

less than 4 miles per hour, being an increase of 2·2 miles per hour. During ebb-tide the surface velocity was 2·7 miles per hour, and at 50 feet it was not less than 4·5 miles per hour, being an increase of 1·8 mile per hour. The existence of these under-currents is due to some obscure causes connected no doubt with the configuration of the bottom, and the circumstances under which the tidal wave approaches and recedes from the shore. The existence of a powerful oceanic under-current during the flood-tide may account for the increased under-velocity of the tide flowing into the Cromarty Firth; and if we suppose a similar rapid under-current to sweep along the coast during the ebb-tide, the tendency would be to draw off the water more quickly from the lower part of the channel between the Suters which forms the mouth of the firth, and thus to increase the velocity at and near the bottom during the ebb-tide, as also indicated by the observations to which we have alluded. It is evident that in all such situations the application of a *common* or *mean* velocity, deduced from the observed surface velocity, cannot be relied on as correct.

As the slopes, velocities, and discharges of rivers are so important in all matters connected with the flow of streams, and may be useful for comparison in considering questions of river engineering, we give at the end of this article, in a tabular form, the physical characteristics of different rivers, embracing all the information we have been able to collect, with the sources from whence that information was obtained.

We have considered it necessary to enter thus far into detail, to prepare the way for what is to follow,—*First*, Because it is quite impossible to consider and design with advantage the improvements of a river without a correct knowledge of its physical characteristics, as developed in

the course of such investigations as we have described. Such information cannot in every case be procured with an equal amount of precision, but the more complete and detailed it is, the more confidently and advantageously will the engineer proceed to form his design. *Secondly*, We have been particular in defining the physical boundaries of rivers, because the remedial means which call for the engineer's consideration in designing improvements on the three compartments which they include, are not less distinct than the different phenomena which have been described as their peculiar characteristics. In proof of this, it may be stated generally, that the works on the "river proper" section consist chiefly in the erection of weirs, by means of which the water is dammed up so as to form stretches of canal in the river's bed, with cuts and locks between the different reaches. The "tidal compartment" embraces a more varied range, including the straightening, widening, or deepening of the courses and beds of rivers, the formation of new cuts, the erection of walls for the guidance of tidal currents, and in some cases the shutting up of subsidiary channels; while the "seaward compartment" embraces all works connected with the improvements or removal of bars and shoals.

On these subjects we shall have to enter at some length; and in treating of them it may be most convenient to consider the question of river navigation under the three following sections, viz.:—

1*st.* The upper compartment, or "river proper."

2*d.* The intermediate compartment, or "tidal river;" and

3*d.* The lower compartment, or "sea proper."

SECTION III.

THE "RIVER PROPER" DEPARTMENT.

Sizes of rivers proportional to the extent of country drained.

The magnitude of a river is, under certain conditions, proportional to the extent of country which is drained, as will be seen by reference to the table at the end of this article, and all our ideas regarding rivers, as affording the means of inland navigation, must necessarily be to some extent varied to meet the different physical characteristics of different countries. Thus, in continents we find rivers of great magnitude, fed by the drainage of vast tracts of surrounding land, rolling their contents in a broad, deep current to the ocean, and affording a highway for vessels of the largest class to pursue their course for hundreds of miles into the interior of the country. Of such is the Mississippi, which, according to Mr Ellet, maintains, for a distance of nearly 1200 miles above New Orleans, an average breadth of 3300 feet, and a depth of 115 feet. The Ohio, which joins it at this place, is navigable to Pittsburgh, where the writer of this article has seen from thirty to forty large-sized steamers lying at the quays of that truly inland port, which were all engaged in trading to New Orleans, on the Gulf of Mexico,[1] being a river navigation of upwards of 2000 miles.

In considering the improvement or maintenance of such a navigation as this, the engineer has to deal chiefly with

[1] *Sketch of Civil Engineering of North America*, by David Stevenson, C.E.

the control of the discharge due to the rains of the district through which the river flows. His difficulty does not so much consist in deficient depth or breadth of navigable channel, as in the magnitude of the floods with which he has to contend, and the provision he has to make for retaining them within such limits as to secure the safety of the surrounding district.

In less extended tracts of country the rivers are proportionally smaller; and when we come to consider our own island, we find that its area and drainage are altogether insufficient to afford depth and breadth of water for extended inland navigation. This will readily be understood when the areas of the basins and the discharges of some of our largest rivers are compared with the Mississippi, to which we have alluded. For example, according to the table to which we have already referred, the Tay drains 2283 square miles, and discharges 274,000 cubic feet per minute; the Clyde drains 945 square miles, and discharges 48,000 cubic feet per minute; the Mississippi drains 1,226,600 square miles, and discharges 76,800,000 cubic feet per minute.

The Mississippi.

It will not, we believe, be considered inappropriate to the subject we are discussing, to offer a short sketch of what is undoubtedly the most gigantic river navigation in the world, taken from the elaborate work by Mr Charles Ellet, on the Mississippi and the Ohio. It appears, from the information given in that work, that the Mississippi varies from 2200 to 5000 feet in width, the average width being assumed as 3300 feet. It is from 70 to 180 feet in depth, the average being 115 feet. The area of the cross section varies from 105,544 square feet to 268,646 square feet, the average being 200,000 square feet. The length, from its junction with the Ohio to the Gulf of Mexico, is

1178 miles, and its average descent at full water is $3\frac{1}{4}$ inches per mile, and in absence of floods (or during summer and autumn) $2\frac{8}{10}$ inches per mile. The length of the Ohio, from its junction with the Mississippi to Pittsburgh (the head of the navigation for large vessels), is 975 miles, and the average inclination is about $5\frac{1}{2}$ inches per mile. From Pittsburgh to Olean Point the distance is 250 miles, and the inclination 2 feet 10 inches per mile. When the water is high, steamboats have ascended to Olean Point, which is 2400 miles from the Gulf of Mexico; and in doing so, have had to overcome a current which at some places runs with a velocity of 5 miles per hour. This, however, is chiefly in the upper part of the river. Generally speaking, vessels have no difficulty, in the lower or more open part of the stream, in avoiding the strength of the currents by keeping in-shore. But in the Ohio much inconvenience is felt during dry seasons from the currents at certain parts of the river; and the writer has seen a steamer, when deeply loaded, unable to overcome them until assisted by a warp attached to an anchor dropped ahead of the vessel, in the middle of the channel, by which, after considerable detention, she was "warped through the rapid." The discharge of the Mississippi is computed by Mr Ellet, at high water, at 1,280,000 cubic feet per second; and its drainage he estimates at 1,226,600 square miles. When the autumnal rains set in, the river rises above its summer level to the enormous extent of about 40 feet at the mouth of the Ohio, and 20 feet at New Orleans. In investigating the physical characteristics of this mighty stream, Mr Ellet found—1*st*, That the average surface velocity in the centre of the river was 5 miles per hour, and occasionally the speed reached 7 miles per hour; 2*d*, By using under-current floats, he found that the speed of a float, supporting

a line of 50 feet long, was always greater than that of the surface float—the average increase of velocity being 2 per cent.; 3*d*, The results of the experiments made, lead him to conclude that the mean velocity of the Mississippi is about 2 per cent. greater than the mean surface velocity; 4*th*, In coming to this conclusion, no account is taken of such observations as show remarkable under-currents, the velocity of which were in some places found to be 17 per cent., and 20½ per cent. greater than the surface velocities; 5*th*, While the mass of water which the channel of the Mississippi bears is running downwards with a central velocity, the current next the shore is sometimes found to be running upwards, or in the opposite direction, at the rate of 1 to 2 miles per hour; 6*th*, While the water is running downwards in the one side of the river, it is often found with an appreciable slope, and visible current running upwards on the other side of the river; 7*th*, The surface of the river is therefore not a plane, but a peculiarly complicated warped surface, varying from point to point, and inclining alternately from side to side. After considering all the conflicting results derived from his investigations, Mr Ellet, in order to obtain the mean velocity and discharge of the river, employed the formula as already noticed,—

$$V = \frac{8}{10}\sqrt{df} + \frac{df}{20}$$

$$M = 0{\cdot}8\ V$$

and $Ma = D$

where V = the velocity of central surface current in feet per second,

d = maximum depth of river in feet at place of observation,

f = slope of surface in feet per mile,

M = the mean velocity in feet per second,

a = area of cross section of river in feet,
D = discharge of river in cubic feet per second.

In discussing the various formulæ for velocities and discharges, we have seen that the formula applied to the Mississippi by Mr Ellet does not apply to such rivers as the Tay, or to smaller water-courses; and until the result which he has given has been compared with the discharge obtained by actual measurement of the velocities at different parts of the cross section, we do not think that the discharge of the Mississippi, which has been calculated by Mr Ellet, can be relied on as accurate.

The chief object of the investigations made by Mr Ellet was the prevention of floods, which have recently increased both in number and extent. This he attributes—

First, To extended cultivation, by which evaporation is supposed to be diminished, the drainage increased, and the floods hurried forward more rapidly into the country below.

Second, To the extension of the embankments along the banks of the Mississippi and its tributaries, by which water that was formerly allowed to spread is now confined to the channel of the river.

Third, To what are termed cut-offs, or straight cuts, by which the distance is shortened, and the slope and velocity increased, so that the water is brought down more rapidly from the country above.

Fourth, To the gradual extension of the delta into the sea, so as to lengthen the lower course of the river, to diminish the slope and velocity, and thus to throw back the water on the land above.

The works suggested for protecting the country against floods are—

First, More sufficient embankments.

Second, The prevention of further cut-offs, or works

for straightening the upper parts of the tributaries of the river.

Third, The enlargement of the seaward channels or outlets; and

Fourth, The creation of large artificial reservoirs, by placing dams across the outlets of the lakes or distant tributaries, so as to compensate for the loss of the natural overflow of the water, which is checked by the embankments for protecting the country in the lower part of the river.

Danube.

An interesting account has been given by Mr Shepherd[1] of certain improvements on the Danube, to which we shall very shortly refer. The navigation of that river was greatly impeded by the constant shifting of its course after every flood. Its channel was divided into numerous branches, and the main object of the improvements was to shut off these lateral branches, and to cause the river to flow in one central channel. This was effected by means of a series of spurs or jetties, made of bundles of brushwood, and thrown out from either side of the river. The brushwood was laid down in its green state, and, taking root, each spur or jetty, after a few years, formed a thick massive hedge, which now prevents the stream from making further ravages on the banks, and confines it to one central channel, scouring out a depth sufficient for navigation. This system of embanking with faggots has been, according to Mr Shepherd, the means of rescuing thousands of acres of land on the Danube, at a cost of not 1s. per acre. These improvements have, it appears, been effected in what were the most dangerous parts of the river, and have, it is stated, in connection with an improved organization of pilotage, been of great benefit to the traffic of the Danube, which is

[1] *Civil Engineers' and Architects' Journal*, vol. xii., p. 321.

now carried on almost uninterruptedly, it being a very rare occurrence to hear of any of the steamers getting aground.

Circumstances of the Mississippi not applicable to this country.

Although it has been considered proper to allude thus briefly to the large continental rivers, yet it will be obvious that the magnitude of such a river as the Mississippi, for example, prevents us from applying the special results and observations of Mr Ellet to rivers in this country. Indeed, the fresh-water or upper compartments of our rivers are so small, and their navigation is so limited, that we have little to say under that head which can be applicable to the British Isles.

Means of rendering our rivers navigable.

Our streams cannot, like the Mississippi or other large rivers, be advantageously navigated in their natural state; and the means employed to render them navigable may be said to consist in throwing dams across their beds, so as to convert them into a succession of narrow lakes or pools, in which the water is dammed up to such a height as to afford sufficient depth for small boats.

Old stanches.

In early times this was effected by means of what were called "stanches." Sir William Cubitt states that when he undertook the improvement of the Stour in Essex, there were thirteen stanches along the course of the river. These stanches consisted of two substantial posts, which were fixed in the bed of the river, at a sufficient distance apart to permit a boat to pass easily between them, and connected at the bottom by a cross cill. Upon one of these posts was a beam turning on a hinge or joint, and long enough to span the opening. When the "stanch" was used, the boatmen turned the beam (which was above the level of the water) across the opening, and placed vertically in the stream a number of narrow planks resting against the bottom cill and the swinging beam, thus forming a weir which raised the water in the stream about 5 feet high. The boards were

then rapidly withdrawn, the swinging beam was turned back, and all the boats which had been collected above were carried by the flow of water over the shallow below. By repeating this operation at given intervals, the boats were enabled to proceed a distance of about 23 miles in two or three days.

Dams and locks.

This primitive system, which was at one period very common in England, has been superseded by throwing permanent dams across the river, so as to convert its channel into a series of deep-water reaches, and the boats pass from one reach to the other by means of side-cuts with locks. The same plan has been extensively carried out in many of the smaller rivers in America, and is there called "still-water navigation." It has been executed on a pretty large scale by Sir William Cubitt on the upper part of the Severn, where the river has been divided into four reaches, having a depth of 6 feet, with side-cuts and locks having a lift of 8 feet each. The difficulty attending such an operation is the impediment which the weirs present to the passage of the river during floods; but in the case of the Severn this difficulty seems to have been overcome. Sir William Cubitt says the object of these weirs was to raise the water, and to retain it at a proper height for the navigation of the shallow parts of the river, without opposing such barriers as should prevent the free discharge of flood-water; and that this end has been completely answered, there being a depth of 6 feet of water at all times where there was formerly only a depth of 18 inches, and during floods the back-water does not rise higher than before the establishment of the weirs. A similar result may, he believes, be always attained by making the obliquity of the weirs sufficiently great.[1] The same system has also been adopted by the late

[1] *Transactions of Institution of Civil Engineers*, vol. v.

Mr Rendel and Mr Beardmore, for the improvement of the navigation of the River Lea, an account of which has been communicated by Mr Beardmore to the Institution of Civil Engineers.[1]

The arguments, however, against canals, in consequence of the greater facilities afforded by railways, seem to apply with equal force to the upper compartments of rivers with their dams and locks; and as it is not likely that such a system of inland navigation will receive much extension, we shall, without further detail, proceed to consider tidal navigations which are more intimately connected with the commercial interests of the British Isles, and consequently occupy a more important position in the hydraulic engineering of this country.

[1] *Transactions of Institution of Civil Engineers*, vol. xiii., p. 241.

SECTION IV.

TIDAL COMPARTMENTS OF RIVERS.

What is meant by the term "tidal."

It is perhaps necessary to preface our observations on this branch of the subject by explaining what is implied by a "tidal navigation," as distinguished from such large fresh-water streams as the Mississippi, or those smaller streams forming the upper compartments of our own rivers, both of which we have been considering. In the former case we saw that the art of navigation is most successfully and extensively practised on the fresh-water streams of the large continental rivers; while in the latter case it was shown that even by the aid of artificial weirs and locks, the largest rivers of this country could only be made navigable for vessels of the smallest class. We learn from this, as has also been stated, that the comparatively limited extent of our isolated country does not afford sufficient area for the collection of so large an amount of rain and spring water as to render our fresh-water streams available for the purposes of navigation. The amount of fresh water which they discharge varies as the river floods rise and fall; and even at its maximum its effects in the lower portion of our estuaries is but feebly felt, as more fully explained hereafter in section vi., under the head of "*Bars*." Our rivers, indeed, may be regarded simply as creeks or inlets, formed and kept open, not by the fresh-water stream alone, but mainly by the action of the tide; and may be said to be navigable only

Its importance.

when their channels are filled by the influx of water from the ocean. The great agent, therefore, in keeping open and deepening our navigations is to be found in the tidal flow, which not only scours and maintains the sea channels of our rivers, but also increases their depth of water. Nor is this all: another most important advantage derived from the tides is that upward current due to the tidal rise, which, at first checking and ultimately overpowering and reversing the flow of the ebb-stream, carries vessels to their port, far, it may be, into the interior, without the aid of either steam or wind. This is a view of the subject which cannot fail to strike even the most superficial observer, when he sees, on the Thames or Mersey, for example, a vast fleet of vessels of all sizes, and from all countries, hurried on by the silent but powerful energy of the flowing tide. How invaluable is such an agent to the commercial interests of this country! If, indeed, the action of our river-tides were suspended, it might truly be said of the steam power employed on our railways, that its occupation would be gone. Nor need we do more to enforce the wide-spread interests of the subject than remind the reader that the ports of London, Liverpool, and Glasgow, not to name less important places, are entirely dependent on tidal navigation for their existence.

Its extent modified by circumstances.

From what has been said as to the physical boundaries of rivers, it will be apparent that the extent to which this tidal influence is felt varies in different situations. Where the slope of the river is gentle, and the channel is comparatively clear and unobstructed, it is felt far up the river, as in the case of the Thames, where it reaches Teddington Weir, 65 miles from the Nore; and in the Tay, where it reaches its junction with the Almond, 35 miles from the bar. In other cases, such as the Lune in Lancashire, or

the Dee in Cheshire, the tidal flow is suddenly checked by artificial weirs erected in the bed of the river for the supply of mills. In a third class of rivers the upward flow of the tide is almost neutralized by the existence of natural obstructions, as in the case of the Erne at Ballyshannon, where it flows only about 3, and the Ness, where it flows only about 6 miles up the river.

The object of all improvements is to increase it.

Now, the great object of the engineer, in dealing with what we have termed the "tidal compartment of a river," is to increase the *tidal influence*, or, in other words, to facilitate the *propagation of the tidal wave* through the estuary or river for which he has to design works, and it will be found in the examples we have hereafter to offer that, with proper management, this desirable improvement may be surely accomplished, and its amount accurately determined. But that the subject may be fully understood, it is necessary that we should in the outset explain the nature and laws of "tidal propagation" and "tidal currents"—phenomena attending the tides of our rivers and estuaries which must be duly recognised and estimated in all designs for improvements which are based on sound principles of river engineering.

The tidal wave.

The tidal wave which enters an estuary is a branch of the great tidal wave of the ocean. Mr Scott Russell was the first experimental inquirer who conducted investigations on the tide wave of estuaries. Mr Russell's observations were made on the Dee in Cheshire, and the Clyde, and the results which he obtained may be briefly stated as follows:—

Laws of its propagation.

1. The great primary wave of translation differs from every other species of wave in its origin, its phenomena, and its laws.

2. The tide wave is *identical* with the great primary wave of translation.

3. In a rectangular channel, the velocity with which the tidal wave is propagated is equal to the velocity acquired by a heavy body falling freely by gravity through a height equal to half the depth of the fluid, reckoned from the top of the wave to the bottom of the channel. In a sloping or triangular channel the velocity is that of a gravitating body due to $\frac{1}{3}$d of the greatest depth. In a parabolic channel the velocity is that due to $\frac{2}{3}$ths or $\frac{8}{10}$ths of the greatest depth, according as the channel is convex or concave. And generally *the velocity is that due to gravity, acting through a height equal to the depth of the centre of gravity of the transverse section of the channel below the surface of the fluid.*

4. The velocity in channels of uniform depth is independent of their breadth.

5. A tidal *bore* is formed when the water is so shallow that the first waves of flood move with a velocity so much less than that due to the succeeding parts of the tidal wave as to be overtaken by the subsequent parts, or whenever the tide rises so rapidly that the height of the first wave of the tide exceeds the depth of water at that place.

6. A wave of high-water of spring tides travels faster than a wave of high-water of neap tides.

These laws are supposed to apply to the passage of the wave through channels having a pretty uniform depth and form of cross section; but the very irregular outline of the beds of most of our tidal channels renders it almost always difficult, and in many cases impossible, to apply them rigidly to cases which occur in actual practice. The writer may, however, state generally, in corroboration of the correctness of Mr Russell's deductions, that after investigating the tidal phenomena of many estuaries and rivers, he has found that in all cases the quickest propagation of the tidal wave

occurs at those places where there is the greatest average depth; but the varying outline of the cross section renders it almost impossible, in most cases, to determine what is the *ruling depth* for calculating the rates of propagation in any particular section of the river. In the Dornoch Firth, to which we have already alluded, the writer found that the distance of 11 miles between Portmahomac and Meikleferry is traversed by the tide-wave in thirty minutes, giving a velocity of 22 miles per hour. The depth of the water of that part of the firth varies from 9 to 50 feet. Between Meikleferry, again, and the Quarry, a distance of 8 miles, where the depth is much less, varying from 6 to 20 feet, the transit of the wave occupies 65 minutes, giving a speed of 6·4 miles per hour.[1] Between the Quarry and Bonar Bridge, a distance of 1 mile, the water is comparatively shallow, varying from 1 to 3 feet, and the rise on the bed of the river is very rapid. In consequence of these obstructions, the tide does not appear at Bonar Bridge for an hour and a half after it has appeared at the Quarry, giving a rate of propagation of only two-thirds of a mile per hour. From observations made by the writer at the Dornoch Firth and elsewhere, it appears evident that, in addition to the elements on which the laws of propagation as quoted are based, the slope on the surface of the stream in tidal rivers affects to some extent the rate of propagation, independently either of the depth or cross-sectional form of the channel; but it will be more convenient to notice this at a subsequent part of this treatise.

Obstacles which operate in retarding tidal wave.

Now, the obstructions which are most frequently found to operate as retarding influences are, the circuitous routes of the channels of rivers, inequalities in their beds, the pro-

[1] The times are the intervals which elapse between the first appearance of the tide at the different stations.

jection of obstacles from their banks, and in certain circumstances the slopes of their surfaces. The combined effect of these obstructions is such as in all rivers to check the propagation of the tide-wave; and in situations where there is a great and rapid rise of tide, to heap up the water in the lower part of the river, and so to occasion what are termed "bores," and other apparent anomalies. In the Dee, for example, there is at low-water a fall of 11 feet from Chester to Flint, a distance of 12 miles; and on one occasion the writer found that after the tide had risen 18 feet 4 inches at Flint, it had not commenced to flow at Chester. While, therefore, at low-water there is a fall seawards of 11 feet from Chester to Flint, there was at the time alluded to a fall from the sea downwards, so to speak, of no less than 7 feet 4 inches from Flint to Chester. Fig. 2 is a diagram

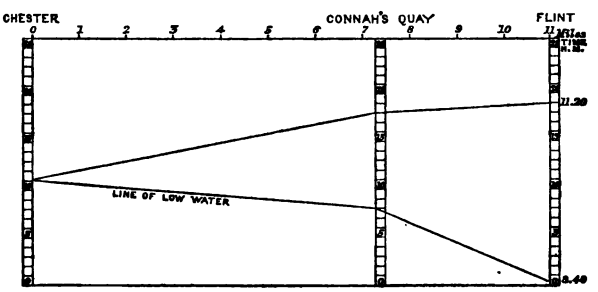


Fig. 2.

of these tide lines, which will illustrate more clearly the effect of this heaping up of water in the seaward part of the river. The lower line represents the surface of low-water, and the upper line shows the surface at the period of flood-tide to which we have alluded.[1] In this case the

[1] The writer has found, that in all cases the heaping up of the

small depth of water, and tortuous and unequal channel, retarded the early waves of flood-tide so much, that they were overtaken by the succeeding waves; and, in accordance with Mr Russell's theory, a *tidal bore* was the result, or, in other words, the water was heaped up so high, and the slope was consequently so great, as to cause the water to tumble over, and ascend the river in the form of a breaking wave.

Example of a tidal bore on the Dee.

The manner in which such tides flow up an estuary may be explained by a simple illustration. In fig. 3 the letters

water increases with the rise of tide, being greatest in spring and least in neap tides; as will be seen from the following tabular views of the maximum difference of level between the surface of the water at Flint and Chester on the Dee, and (to offer another example) at Glasson and Lancaster on the Lune, during the flow of tides of various amounts of vertical range.

River Dee.		
Date.	Rise of tide at Flint.	Maximum fall from Flint to Chester.
1839.	Ft. in.	Ft. in.
May 21	14 0	3 8
„ 23	15 6	4 5
„ 25	16 4	5 8
„ 29	18 0	6 6
June 10	19 8	7 10

River Lune.		
Date.	Rise of tide at Glasson.	Maximum fall from Glasson to Lancaster.
1838.	Ft. in.	Ft. in.
Aug. 29	12 1	1 1
„ 31	12 9	1 6
Sept. 1	15 4	2 0
„ 3	19 8	2 10
„ 5	23 2	3 2
„ 6	23 6	4 4

a, *b*, *c*, *d* represent a part of the low-water channel of the River Dee, at a place where the estuary is about 3 miles wide, and consists of extensive sand-banks. In examining minutely the windings of the stream in reference to certain investi-

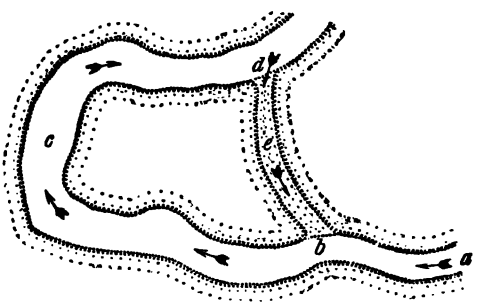


Fig. 8.

gations, it was necessary to walk down the right bank of the river at low-water, close to the edge of the channel. While so engaged, the writer crossed at the point *b*, a hollow in the sand-bank, which, though depressed below the general height of the surrounding surface, was nevertheless quite dry, the lowest part of the track being considerably above the level of the water of the river. Crossing this hollow, the noise of the approaching tide was heard; and expecting to meet the flood forcing its way up the river, he continued to walk on; but seeing no appearance of its approach by the proper channel, and still hearing the noise gradually increasing, and apparently coming from behind, he turned round and perceived a rapid run of water flowing (in the direction shown by the arrow) through the hollow *deb*, which had just been crossed, and emptying itself into the river at *b*. He immediately hastened back, and after having waded through the newly-formed stream at *b*, which

had attained a depth of 6 or 8 inches, he remained on its upper side to see the result of this unexpected inroad. The water continued to rush through the hollow, rapidly gaining breadth and depth, and at last, after an interval of 2 or 2½ minutes from the time at which the noise was first heard, the tide appeared forcing its way up the proper channel of the river with a head or bore of 6 or 8 inches in height. In this case it is clear, from what has been said as to the slope on the river from Flint to Chester during the early periods of tide, that the level of the water at *d* in the dia gram would be above that at *b*. The tide, on arriving at the point *d*, would be naturally divided into two branches or currents, one proceeding up the natural channel towards *c*, and the other flowing into the hollow in the sand-bank at *d* towards *e*; and as the level of the water at *d* rose, the stream which flowed into the hollow in the sand-bank would gradually rise higher until it surmounted the summit-level at *e*, after which it would rush from *e* to *b* without obstruction. The other branch of the tide would in the meantime be forcing its way along the circuitous channel *dcb*, which was about a mile in length; and before it reached *b*, the water at *d* had attained a much higher level than at *b*, and having surmounted the summit-level of the sand-bank at *e*, continued to flow without obstruction into the channel of the river in the manner represented. Thus in all places where the retarding influences which exist in the regular channel of the river exceed the obstructions in any *back lake* or *swash-way*, the tide will flow sooner through the latter than the former, and give rise to an apparent anomaly such as has been described.

Bore on the Severn.

The late Admiral Beechey, in his *Remarks on the Tidal Phenomena of the River Severn*, published in 1851, gives the following interesting account of the bore on that river:

—"The bore," he says, "is not dangerous to boats if afloat in the middle of the river; and it is the common practice up the Severn to row the boats out to the centre of the stream on the approach of the bore, and put their head to the wave; but if this precaution be not taken, and the boats are allowed to remain at the edge of the shore, they are liable to be swamped or stove, as the waves break with great violence along the banks as it proceeds; but towards the centre of the river, if the water be not very shallow, the wave is smooth and unbroken. Before the arrival of the bore, the stream runs down the river, and the altitude of the water at a distance from the sea is quite stationary; but on the arrival of the bore, the water instantly rises according to the height of the breast of the wave, and the stream turns and follows the wave up the river, although it had but a few minutes before been running down at a rapid rate; and this change of stream is effected without any breaking wave. When there is a heavy fresh down the river, and the stream is running at the rate of four or more miles an hour, the upward stream hangs for several minutes after the bore has passed, not being able to overcome at the moment the impetus of the ebbing water; but when it has once turned upwards, it attains its maximum speed in the first half hour of the tide. When the reaches of the river are straight, the bore travels evenly up the river, but at the turnings it is thrown off towards the further side, where it rises higher than in the straight reaches; thence it recoils and impinges upon the opposite shore, and so, like a disturbed pendulum, it oscillates from side to side, and only regains its steady course when the reaches lengthen. The highest tide of the year rolled up the Severn on the 1st of December. There was about 2 feet of water above the ordinary summer-level in the river, and

the morning was calm and favourable to the phenomenon. The stream at low-water ran down at the rate of 2½ miles (geographical) per hour, until the time when the bore came rolling up the river with a breast from 5 to 6 feet high at the sides, and 3 feet 6 inches in the centre. The wave was glassy smooth; and as it advanced towards a spectator stationed at Stonebench, a singular effect was produced by the distorted surface of the wave reflecting the rising sun, and brilliantly illuminating the stems and branches of the wood skirting the river as the bore passed along—an effect which greatly enhanced the interest of the phenomenon, which is at all times an object of curiosity. The stream turned up the instant after the bore passed, and ran at the rate of 3¾ miles per hour, which was about half the average rate of the bore, the speed of which varied from 12 to 7 miles per hour, averaging 8 between Stonebench and Gloucester." Admiral Beechey further says, "that the effect of a fresh, or a certain depth of water in the river, upon the advance of the bore is remarkable. At dry periods the great obstruction to the progress of the bore lies between Sharpness and Bollowpool, and at such times the many dry sand-banks prevent the bore attaining a rate greater than about 4 miles an hour; but when the river is under the influence of freshes, and the water raised and covering some of the banks, it appears to roll on at a rate of 10 miles an hour in opposition to the stream, which runs down at the rate of upwards of 4 miles an hour."

Tide currents.

But the passage of the tidal-wave through an estuary or river, must not be mistaken for what is called the "tide current," which is a totally different phenomenon. The tidal-wave which we have been describing as passing through the lower part of the Dornoch Firth, for example, at the rate of 22 miles per hour, is not the current due to

the flowing tide by which vessels are carried across the bar, and borne onward to their destination. That current flows with a velocity which at the Dornoch Firth does not exceed 4 or 5 miles per hour; a velocity which, indeed, is not often exceeded, excepting in such rapid tideways as the Severn, at the New Passage, where the velocity is said to reach 9 miles per hour;[1] and in the Pentland Firth, where Captain Otter measured a velocity during ebb-tide of no less than $10\frac{6}{10}$th nautical miles per hour,[2] being, so far as we know, the greatest tide velocity on record. The laws of the propagation of the tidal wave, to which we first alluded, depend, as explained, on circumstances somewhat obscure; but the velocity of the tide current, or that current which flows into our rivers, and affects the transit of shipping, is due *entirely* to the *slope* or *fall* on *the surface of the water.* The amount of this slope has been shown to be dependent on the rapidity with which the tide rises, and the amount of obstruction presented to its propagation up the river. The more rapid the rise of tide, and the greater the obstruction to its flow, the higher will the tide-wave at certain parts of a river or estuary be heaped up. A head of water is thus formed whose height is due to the rapidity of the rise of the tide and the obstruction to its progress; and a flow of water having a velocity due to that head is generated up the river or estuary, and this flow of water is what we term the *tide current.*

By increasing the rate of tidal propagation the velocity of the tidal currents is decreased.

This is probably the most convenient place to notice some facts of great importance in river engineering, which we deduce from these considerations, as to the nature of

[1] *Report to the Admiralty on the Severn Improvement Bill,* 1849, by Captain Vetch.

[2] *Admiralty Survey of Pentland Firth,* by Captain Otter, and Admiralty North Sea pilot.

the tidal propagation and tide currents. The obstructions to which we have alluded *retard* the rate of propagation, but by raising the head, they *increase* the velocity of the tide currents. Now, as the aim, and, if successful, the effect of all engineering works, is to increase the rate of tidal propagation, no less certainly will they tend to lessen the heaping up of water in the lower reaches, and at the same time to *decrease the velocity of the tide currents.* In cases where these currents are found to act prejudicially by producing a bore, or by bringing up sand from the lower parts of the estuary, or where they are inconveniently rapid for navigation, we are thus, while increasing the propagation of the tidal wave, enabled to check their energy, and thus to effect an important improvement.

The level of high-water not raised by facilitating tidal propagation.

Another important circumstance is worthy of notice at this place. It is well known that the momentum of the column of water, flowing up the gradually contracting and rising channel of a river, causes the level of high-water to stand higher than in the open ocean or in the lower reaches. This is accounted for, as already stated, on the principle of the conservation of forces. The height to which the water is thus raised depends on the quantity of water thrown in by the tide during a given time, the elevation being greatest at spring, and smallest at neap tides. At the Dee, for example, the writer found that the high-water of spring tides at Chester was 14 inches higher than that at Connah's Quay; while at neap tides the difference of level was only 4 inches. Now, the effect of engineering works, as will be more fully detailed hereafter, is not only to produce a free propagation of the tide, but to admit a larger body of tidal water; and it has been contended that such operations must necessarily cause the tide to rise higher, and it has been attempted to be shown that they

might in some situations occasion inconvenience, and even injury to property, in consequence of the overflowing of the river's banks. After the most careful observation, however, the writer has not been able to detect that such operations have in any case had the effect of appreciably raising the level of the high-water line. Although the tide in improved rivers begins to flow earlier, and a much larger body of water is thrown up the river, still, in conformity with the views already stated, the velocity with which the water flows is decreased, so that the momentum of the column of water remains nearly the same, or at least is not so notably altered as sensibly to increase the height to which the high-water rises; and by this fortunate compensative action our rivers, though their beds are opened up and improved, do not inundate our towns or even overflow our quays, but quietly keep within their original limits.

Removal of obstructions to tidal flow.

The removal of all obstacles to the flow of the tide is the object, as already stated, to which the engineer has chiefly to direct his attention in designing improvements in the department of navigation now under consideration; and it may be stated, that in order to form a satisfactory opinion on this matter, it is essential to have an accurate survey, showing the depths of water and the breadths of channel throughout the whole extent of the river, and also to ascertain the amount of tidal range, the velocity of the currents, the rise on the bed, and the nature of the materials of which the bottom and banks are composed. Possessed of this information, he is in a position to consider to what extent the bed of the river may with advantage be deepened and widened, and the currents directed by means of walls; also if subsidiary channels may with safety be shut up, or new cuts be made for the passage of the river, or whether or not irregularities in the width which injuriously

affect the currents may be corrected. In all these matters the engineer must, in each particular case, be guided by experience. While it is therefore impossible, in such circumstances to specify works which shall be of *universal* application, it is nevertheless quite within the range of sound engineering advice to point out *generally* the works which are most likely to effect improvements, and to direct the reader to cases in which such works have proved successful; and this is all that we propose to do in the remarks we have to offer on this part of our subject.

With reference to these operations, then, it may be stated, that all obstructions which prevent the extension of the tidal influence up the river may safely be taken away, and their removal may confidently be expected to be followed by highly beneficial effects. It is necessary to remark, however, that the removal of artificial weirs erected for the purposes of manufacture is, in many cases, attended with difficulty, arising from the value of the interests involved, which are sometimes so great that the abolition of such erections cannot be effected without large compensation. The weirs on the Dee in Cheshire, and the Lune in Lancashire, are instances of this, being productive of much injury; while in both cases the interests affected are so important, and the consequences so serious, as hitherto to have operated as an effectual barrier to their removal. The removal of existing quays and other works of long standing, as in the case of the Thames, the Tyne, and the Wear, is also for the same reason difficult, and works must therefore be designed for such localities which shall not injuriously affect existing interests. But all natural weirs or shoals, consisting of fixed rock or hard gravel, which cannot be disturbed by the action of the current, as well as all projections into the stream,

where unattended by the difficulties alluded to, should at once be removed. Whenever it is possible, divided currents should be united into one stream. The channel, where it is necessary, should be guided by longitudinal walls, and the river's bed should be deepened to the full extent compatible with a due amount of slope being left on the surface.

These may be said to be the safest and most beneficial works which can be adopted in designing river improvements, their effect being to cause the currents of flood and ebb tide to flow always in one channel, and thus to exert their full and combined power in keeping open one navigable track. The manner in which they are executed demands a few remarks; and we shall treat the different works under the heads of:—

1. Removal of lateral obstructions.
2. Closing subsidiary channels.
3. Dredging.
4. Excavation.
5. River walls; and
6. Scouring.

1. *Removal of Lateral Obstructions.*

Under the "Removal of Lateral Obstructions" may be classed all those works which have for their object the formation of proper outlines for the banks or sides of the river.

Jetties objectionable.

In the early history of river engineering it was not uncommon to construct jetties or groins projecting from the banks on either side, with the view of narrowing the stream and producing a greater scouring power to operate on the bottom. It is no doubt true, that such projections have the effect of producing a *local* acceleration of the currents, and in soft

bottoms a corresponding increase of depth in their immediate vicinity. But this increase of velocity and depth being due entirely to the obstruction and consequent raising of the level of the water caused by the jetty, is strictly local. Whenever the water passes the head of the jetty, it expands into the greater width of bed, the head is reduced, a stagnation or eddy takes places, and a bank or shoal is formed,—a result which invariably follows the projection of any obstruction or foreign body into a stream having a soft bottom. As an aggravated instance of the effect of such obstructions, we may refer to the case of a vessel of about 170 tons, which, in consequence of the breaking of a towline, grounded at the side of the River Tay when there was

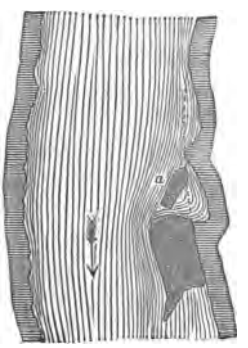


Fig. 4.

some flood in the river. The effect is shown in fig. 4, where the vessel is represented at *a* as lying in a pool which was scoured to the depth of about 10 feet in the course of a few tides; and the gravel thus excavated by the current, acting on the grounded vessel, and amounting to upwards of 1000 tons, was deposited in the form of a

bank, 5 feet above low-water, immediately below the pool, as shown in hatched lines. A similar effect, though varying in degree, occurs in all rivers confined by jetties. The beds of rivers so treated consist of an alternation of shoals nearly dry at low-water, and pools of a depth far greater than is actually requisite, instead of presenting, as they ought to do, a regular bottom and a uniform depth of water available for the purposes of navigation. Examples of the prejudicial effect of jetties are to be met with in the history of the Clyde, the Ribble, the Dee in Cheshire, the Tay, and, the writer believes, with little or no exception, in every situation where the system of contracting, or even directing the currents by means of such works, has been generally adopted. From the Clyde, the Ribble, and the Tay they have been entirely removed. The writer has invariably found, that wherever jetties existed, their entire or partial removal formed one of the first steps towards an improvement of the navigation, and this course has, in all cases which have come within his experience, been followed by good results. In some instances, where the river is contracted by the projection of quays or by the natural formation of the banks, it is desirable, where it can be done consistently with existing interests, to enlarge the cross-sectional area, in order to reduce the velocity of the currents and prevent disturbance of the tidal flow.

2. *Closing Subsidiary Channels.*

The next work to be noticed is the closing of what we term subsidiary channels. These are channels, or, as they are sometimes called, *back lakes*, caused by islands which divide the stream and reduce its scouring power. The consequence is, that instead of flowing in one broad, deep,

navigable bed, kept open by the whole available scouring power, the river is divided into two shallow channels, neither of them affording a good navigation, while frequently a ford or shallow is occasioned both above and below the island by the disturbance which occurs at the junction of the divided currents. On the Tay and the Lune several such secondary channels were, with much advantage to the navigation, closed up by means of embankments formed of gravel dredged from the river, while the other or principal channel was enlarged and deepened, so as fully to compensate for the closing of the smaller channel, and assimilate its cross-sectional area to the rest of the navigable track.

3. *Dredging.*

The introduction of mechanical appliances for the purpose of excavating materials under water, raising them to the surface, and depositing them in barges, was an important era in canal and river engineering. The first employment of machinery to effect this important object is, like the discovery of the canal lock, claimed alike for Holland and Italy, in both of which countries dredging is believed to have been practised before it was introduced into Britain. The moving power at first employed in conducting the process was manual labour, but in all large works dredging is now performed by steam, and is probably the most effective and generally applicable means of improvement at the command of the engineer. The Dutch, at a very early period, employed what is termed the "bag and spoon" dredge for cleaning their canals. It consisted of a ring of iron about 2 feet in diameter, flattened and steeled for about one-third of its circumference; to this ring a bag of strong leather was attached by means of thongs, and

the whole apparatus was fixed to a long pole, which, on being used, was lowered to the bottom from the end of a barge moored in the canal or river. A rope made fast to the iron ring was then wound up by a windlass placed at the other end of the barge, and the spoon was thus dragged along the bottom, and was guided in its progress by a man who held the pole. When the spoon reached the end of the barge where the windlass was placed, the winding was still continued, and it was raised to the surface, bringing with it the stuff excavated, and deposited in the bag during its progress along the bottom. The windlass being still wrought, the whole was raised to the gunwale of the barge, and the bag being emptied, was again lowered and hauled back to the opposite end of the barge for another supply. This system is slow, and only adapted to a limited depth of water and a soft bottom. It has, however, been generally employed in canals, and was much used in the Thames; and the writer, in one situation where, from want of space and other peculiarities, more perfect mechanical means could not be employed, used it to a pretty large extent, the quantity raised being about 135,000 tons. The process, although tedious, was very convenient, and the cost of raising the materials did not exceed 7½d. per ton. Another plan practised at an early period was to moor two large barges, one on either side of the river; between them was slung an iron bucket or box, attached to both barges by chains wound round the barrel of a powerful crab-winch in one barge, and round a capstan in the other. The bucket was lowered at the side of the barge in which was the capstan, and being drawn across the bottom by the crab in the opposite barge, was raised and emptied; after which it was again lowered, and hauled across by the capstan for a repetition of the process. But in all

large operations these and other primitive appliances have, as already stated, been superseded by the steam-dredge, which was first employed, it is believed, in deepening the Wear at Sunderland, about the year 1796. This machine was made for Mr Grimshaw by Bolton and Watt.[1] Receiving improvements from Mr Hughes, Mr Rennie, Mr Jessop, and others, the steam-dredge, as now generally constructed, is a most efficient machine, excavating and raising materials from the depths of 15 to 20 feet of water, at a cost not very different from that at which the same work could be performed on dry land.

For details as to the construction of steam-dredges, we have to refer to the articles in *Weale's Quarterly Papers*, already quoted. As to the nature and extent of work performed by them, we may state generally, that almost all materials, excepting rock or very large boulders, may be dredged with ease. Loose gravel is probably the most favourable material to work in; but a powerful dredge will readily break up and raise indurated beds of gravel, clay, and boulders. In such cases it is usual to alternate on the bucket-frame, a bucket of sheet-iron for raising the stuff, with a rake or pronged instrument for disturbing the bottom. Hand-dredges have been used by Messrs Stevenson at several harbours, by means of which, even disintegrated or rotten rock has been easily raised; and the writer believes, that in very many cases the surfaces of submerged rocks near the mouths of harbours may, by means of such machines, be broken up and removed, so as to obtain in certain situations a considerable increase of depth, without re-

[1] *Encyclopædia of Civil Engineering*, by Edward Cresy, London, 1847; "The Dredging Machine," *Weale's Quarterly Papers*, part i., London, 1843; *The Improvement of the Port of London*, by R. Dodd, Engineer, 1798.

course to coffer-dams, which, on exposed coasts, involve great expense and sea risk, as well as interruption to the trade. These small dredges are worked by eight or ten men, and cost about L.350.

A well-constructed steam-dredge of 16 horse-power will, under favourable circumstances, raise about 140 tons of stuff per hour. The excavated materials are first discharged into lighters or barges, and then deposited in any convenient position, where they are sufficiently removed from the risk of being carried off by floods, and again thrown into the bed of the river.

In some cases the discharge is made into hopper punts or barges, which are floated out to sea, and the stuff is dropped in deep water. The cost of steam-dredging varies according to the nature of the materials and the circumstances of working, as regulated by the tides and the distance of deposit. It has, in the writer's own experience, varied from 4d. to 6d. per ton, or from 5½d. to 8d. per cubic yard, including all expenses.[1] We believe that in no place has steam-dredging been more extensively used than in the Clyde, where the navigable depth has been increased and is maintained mainly by that process. The following details as to the dredging on that river are given in a communication made to the Institute of France by the late Mr William Bald, who acted as resident engineer on the Clyde.[2] Mr Bald says, that annual dredging to the amount of from 160,000 to 180,000 tons was necessary at the time he wrote, in order to maintain the navigable depth of water in the Clyde in the 18 miles from Glasgow seawards. In executing this work, the river trustees employed 5 dredges, a

[1] It was found on the Tay that 18 cubic feet of gravel weighed 1 ton.

[2] *Civil Engineers' and Architects' Journal* for August 1845.

steam-tug, 2 diving-bells, and 160 punts; the whole value of the working machinery being about L.39,000. The following table gives the details of the dredging-machines:—

Details of Dredging-Machines used in deepening the Channel of the River Clyde.

No. of Dredge.	When she commenced to work.	Greatest depth of Working.	Least depth of Working.	Diameter of Cylinder.	Length of Stroke.	Number of Buckets.	Length of Bucket-frame.	Nominal Power of Engine.
		Ft. in.	Ft. in.	Inches.	Ft. in.		Ft. in.	Ho.-power.
1	1824	10 6	3 9	21	2 6	31	47 9	12
2	1826	14 0	4 0	24	2 6	33	52 11	16
3	1830	14 0	4 0	24	2 6	33	52 11	16
4	1836	15 6	4 3	26	2 6	34	54 7½	20
5	1841	17 to 19 ft.	4 4	27½	2 6	34	58 0	22

All these dredges had governors, which regulated the speed to about 28 strokes per minute in ordinary working stuff. The average pressure in the boilers was about 3½ lb. per square inch. In general, 14 buckets were discharged per minute. The speed of the buckets on the frames of dredges Nos. 1, 2, 3, and 4, was 48 feet 5 inches per minute, and that on No. 5 was 49 feet 8 inches per minute. They consumed from 15½ to 18 lb. of coal per horse-power per hour. The following is a statement of the amount of work which was performed by these dredges, and the expense of the process:—

Year ending	Amount expended.			Cubic yds. excavated.	Rate per Cubic Yard.		
	L.	s.	d.		L.	s.	d.
December 25, 1841....	11,841	18	2	218,110	0	1	1
... 24, 1842....	13,612	11	3	313,810	0	0	10½
... 23, 1843....	9,742	7	6½	294,440	0	0	8
... 21, 1844....	10,659	3	8	317,660	0	0	8

Mr Murray gives the following tabular view of the dredging of the Wear at Sunderland, which is also an interesting record of the quantity and cost of material raised by a dredging-machine; but this view is not given by way of comparison with the preceding, as there is little analogy between the cases. The contracted state of the Clyde, the frequent interruptions to which the work was subject by the constant passage of vessels, and the expense of removing and depositing the stuff, necessarily increased the cost of executing the work in that situation.

Tabular View of the Dredging of the Wear at Sunderland in 1842–46.

Date.	Total Quantity Raised per Annum.	Expenditure in Labour for Raising and Depositing per Annum.	Expense of Fuel per Annum.	Expenditure in Labour for Repairs per Annum.	Expenditure in Materials for Repairs per Annum.	Total Expenditure per Annum.	Average cost per Ton on the Year's Expenditure.
	Tons.	L. s. d.	L. s. d.	L. s. d.	L. s. d.	L. s. d.	Pence.
1842	128,245	922 1 2	111 0 0	754 16 0	704 17 11	2492 15 1	4·665
1843	141,325	879 16 0	70 0 0	503 13 4	786 13 11	2240 3 3	3·804
1844	90,980	567 13 4	66 5 9	259 2 1	563 9 10	1456 11 0	3·842
1845	101,075	721 9 0	66 7 6	336 8 0	527 7 10	1651 12 4	3·921
1846	140,350	724 5 4	58 2 5	500 17 2	520 3 2	1803 8 1	3·083
	Hence the average cost per ton on five years' work—						
1842 to 1846	For raising and depositing at sea						= 1·528
	For fuel						= 0·149
	For labour in repairs						= 0·943
	For materials to ditto						= 1·243
	Average total Expenditure						= 3·863

In river-dredging two systems are pursued; one plan consists in excavating a series of longitudinal furrows parallel to the axis of the stream, the other in dredging cross furrows from side to side of the river. It is found that inequalities are left between the longitudinal furrows, when that system is practised, which do not occur to the same extent in side or *cross-dredging*; and the writer has invariably found cross-dredging to leave the most uniform bottom. To explain the difference between the two systems of dredging, it may be stated, that in either case the dredge is moored from the head and stern by chains about 250 fathoms in length. These chains in improved dredges are wound round windlasses worked by the engine, so that the vessel can be moved ahead or astern, by simply throwing them into or out of gear. In longitudinal dredging, the vessel is worked forward by the head chain, while the buckets are at the same time performing the excavation; so that a longitudinal trench is made in the bottom of the river. When the dredge has proceeded a certain length, it is stopped and permitted to drop down and commence a new longitudinal furrow parallel to the former one. In cross-dredging, on the other hand, the vessel is supplied with two additional moorings, one at either side, and these chains are, like the head and stern chains, wound round barrels wrought by the engine. In commencing to work by cross-dredging, we may suppose the vessel to be at one side of the channel to be excavated. The bucket-frame is set in motion, but instead of the dredge being drawn forward by the head chain, she is drawn to the opposite side of the river by the side chain, and having reached the extent of her work in that direction, she is then drawn a few feet forward by the head chain; and the bucket-frame being still in motion, the vessel is hauled back again by

Cross-dredging.

the opposite side chains to the side from whence she started. By means of this transverse motion of the dredge, a series of cross furrows is made ; she takes out the whole excavation from side to side as she goes on, and leaves no protuberances such as are found to exist between the furrows of longitudinal dredging, even where it is executed with great care. The two systems will be best explained by reference to the annexed cut (fig. 5), where AB repre-

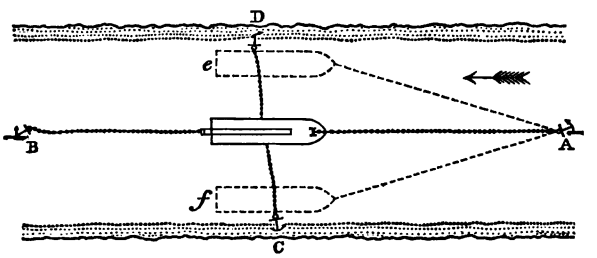


Fig. 5.

sents the head and stern moorings, and DC the side moorings; the arc *ef* represents the course of the vessel in cross-dredging; while in longitudinal dredging, as already explained, she is drawn forward towards A, and again dropped down to commence a new longitudinal furrow.

In some cases, however, the bottom is found to be too hard to be dredged until it has been to some extent loosened and broken up. Thus at Newry, Mr Rennie, after blasting the bottom in a depth of from 6 to 8 feet at low-water, then removed the material by dredging, at an expense of from 4s. to 5s. per cubic yard. The same process was adopted by Messrs Stevenson at the bar of the Erne at Ballyshannon, where, in a situation exposed to a heavy sea, large quantities of boulder stones were blasted, and afterwards raised by a dredger worked by hand, at a

cost of about 10s. 6d. per cubic yard. But the most extensive application of blasting, preparatory to dredging, of which the writer is aware, was that on the works for improving the Severn, by Sir William Cubitt, of which an interesting and instructive account is given by Mr George Edwards, in a paper addressed to the Institution of Civil Engineers, from which the following particulars are taken:[1]—

"It appears that a succession of marl beds, varying from 100 yards to half a mile in length, were found in the channel of the Severn, which proved too hard for being dredged, the whole quantity that could be raised being only 50 or 60 tons per day; while the machinery of the dredges employed was constantly giving way. Attempts were first made to drive iron rods into the marl bed, and to break it up; a second attempt was made to loosen it by dragging across its surface an instrument like a strong plough. But these plans proving unsuccessful, it was determined to blast the whole surface to be operated on. The marl was very dense, its weight being 146 lb. per cubic foot;[2] and it was determined to drill perpendicular bores, 6 feet apart, to the depth of 2 feet below the level of the bottom to be dredged out. The bores were made in the following manner, from floating rafts moored in the river:—Pipes of $\frac{3}{16}$-inch wrought-iron, $3\frac{1}{2}$ inches diameter, were driven a few inches into the marl. Through these pipes holes were bored, first with a $1\frac{1}{2}$-inch jumper, and then with an auger. The holes were bored 2 feet below the proposed bottom of the dredging, as it was expected that each shot would dislocate or break in pieces

[1] "Account of Blasting on the Severn," by George Edwards, C.E. (*Trans. of Institution of Civil Engineers*, vol. iv., p. 361).

[2] Clay weighs about 109 lb., and sandstone about 155 lb. per cubic foot.

a mass of marl of a conical form, of which the bore-hole would be the centre and its bottom the apex; so that the adjoining shots would leave between them a pyramidal

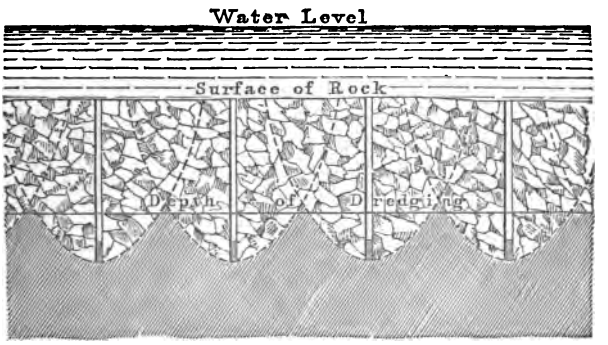


Fig. 6.

piece of marl, where the powder would have produced little or no effect. By carrying the shot-holes lower than the intended dredging, the apex only of this pyramid was left to be removed; and in practice this was found to form but a small impediment. Fig. 6 is a section of the bore-holes; and fig. 7 a plan, in which the inner dotted circles represent the diameters of the broken spaces at the level of the bottom of dredging. The cartridges were formed in the ordinary way, with canvas, and fired with Pickford's fuse. The weight of powder used for bore-holes of 4 feet, 4 feet 6 inches, and 5 feet, were respectively 2 lb., 3 lb., and 4 lb. The effect of the shot was generally to lift the pipes a few inches, which were secured by ropes to the rafts. Mr Edwards says that not one in a hundred shots missed fire, and these shots were generally saved by the following singular expedient:—The pointed end of an iron bar, $\frac{5}{8}$-inch diameter, was made red-hot, and being put quickly through

the water, and driven through the tamping as rapidly as

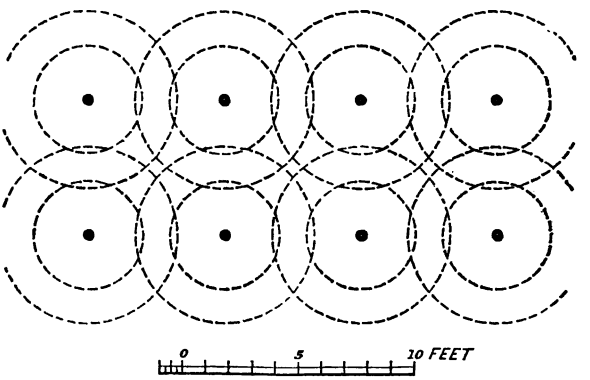


Fig. 7.

possible, was in nine cases out of ten sufficiently hot to ignite the gunpowder and fire the shot.

" The cost of each shot is calculated as follows :—

Use of material	£0	1	0
Labour	0	3	3
Pitched bag for charge	0	0	3
3 lb. of powder at 5½d	0	1	4½
15 feet of patent fuse at $\frac{8}{10}$ths of a penny	0	0	9
Pitch, tallow, twine, coals, &c	0	0	4½
Cost per shot	£0	7	0

Each shot loosened and prepared for dredging about 4 cubic yards ; so that the cost for blasting was 1s. 9d. per yard. The cost of dredging the material, after it had been thus prepared, was 2s. 3d. ; making the whole charge for removing the marl 4s. per cubic yard."

4. *Excavation.*

But there are cases where the bottom cannot be advantageously operated on by any of the means we have mentioned, and where it is necessary to have recourse to other appliances for its removal, such as the diving-bell or diving-helmet, and coffer-dams. The diving-bell has, in conjunction with dredging, been much used on the Clyde, and Mr Bald gives the following account of the operation as conducted on that river:— By diving-bell.

"Between Erskine Ferry and the New Shot Isle the bed of the Clyde, for a distance of 2000 yards, was greatly encumbered with stones and stone boulders, which were highly injurious to vessels if they grounded there; and frequently large ships, in being tugged through this part of the river-channel, had their copper bottoms injured when they touched the rocky channel-bed. In deepening and clearing this part of the river, two diving-bells were employed, and one, and sometimes two, steam-dredgers. The clearing and deepening of this channel was exceedingly severe on the machinery and working-gear of the steam-dredgers; the speed of the engines was therefore governed by the nature of the material in the bottom; and although the iron-work frequently gave way, yet spare links and buckets being always ready to replace those which broke, there was little interruption to the continuous working of the dredgers. When the dredgers had cleared away the material which covered the boulders in the bottom of the channel, the diving-bell boats were worked over the ground so cleared, removing all the larger boulders; and when that part of the channel had been cleared of them, the dredgers went again over the same bottom, removing all the lighter material from the

heads of the lower boulders, preparatory to the bells commencing again; and these operations were continued until the necessary depth was attained.

"The buckets of the steam-dredgers, in working along the bottom, always slipped over the head of the large boulders, which the diving-bells alone could lift and remove. Some of these masses of trap or whinstone were 4 and 5 tons in weight, and from their rounded forms and smooth surfaces, it was evident that they had been brought from some distance. Some of them were of sandstone, but they were more angular than the trap boulders. Quantities of these boulders, lifted from the bed of the channel, might be seen lying along the sides of the river; and many of them had since been split and broken up by gunpowder for repairing the river dykes. The tops of some of the large stone boulders lifted from the bed of the channel were found grooved to a depth of about an inch or more, by the ship's keels having been rubbing over them; and metallic particles were distinctly to be seen upon their surface. In removing these stone boulders from the bed of the channel, the diving-bell men found numerous fragments of copper and iron which had been torn off the ship's bottoms and keels by the large stones; but latterly this had not been the case, as great progress had been made in the removal of the boulders, and the deepening of the channel."

By floatation.

Large isolated masses of stone have also been removed *en masse* from many rivers by fixing louises in them, and raising them by floatation. On the Tay this was done to some extent, and one boulder of 50 tons was raised from the river by that means. Where a large area and considerable depth of solid rock has to be removed, coffer-dams are doubtless the best means of executing the work; but

the chief difficulty in employing dams in the narrow channels of rivers is the obstruction which they necessarily present to the passage of floods and also to shipping. It is therefore a matter of high importance to reduce their bulk to the smallest possible limits. With this view the writer[1] designed a coffer-dam for the works of the River Ribble, which consisted of two rows of iron rods, 3 feet apart, jumped into the rocky bottom, and supporting two linings of planking, the intermediate space being filled with clay, and the whole structure being stayed from the inside, so as to present no obstruction beyond the outer line of the dam. Three dams of this construction were formed in the Ribble; and by means of them, a bed of rock, 300 yards in length, and of a maximum depth of 13 feet 6 inches, was successfully excavated. The maximum depth of water at high-water against the dam was 16 feet, but in very high floods of the river the whole dam was sometimes completely submerged; but on the water subsiding, it was found that the iron rods, on which alone its stability depended, although only jumped 15 inches into the rock, were not drawn from their fixtures. As this construction of dam completely overcomes the difficulty of fixtures in a hard bottom, where piles cannot be driven, and offers very little obstruction to the navigation; and moreover, as it has been successfully used on a large scale, and seems to fulfil all the conditions demanded in such a situation, it may be perhaps considered generally applicable to situations where there is a hard bottom and limited space. The sketch (fig. 8) shows, by an elevation, section, and plan, the manner in which it was constructed.

By coffer-dams.

[1] "Description of a Coffer-Dam adapted to a Hard Bottom," by David Stevenson, C.E. (*Trans. of Inst. of Civil Engineers*, vol. iii., p. 377).

Coffer-Dam for a hard bottom.

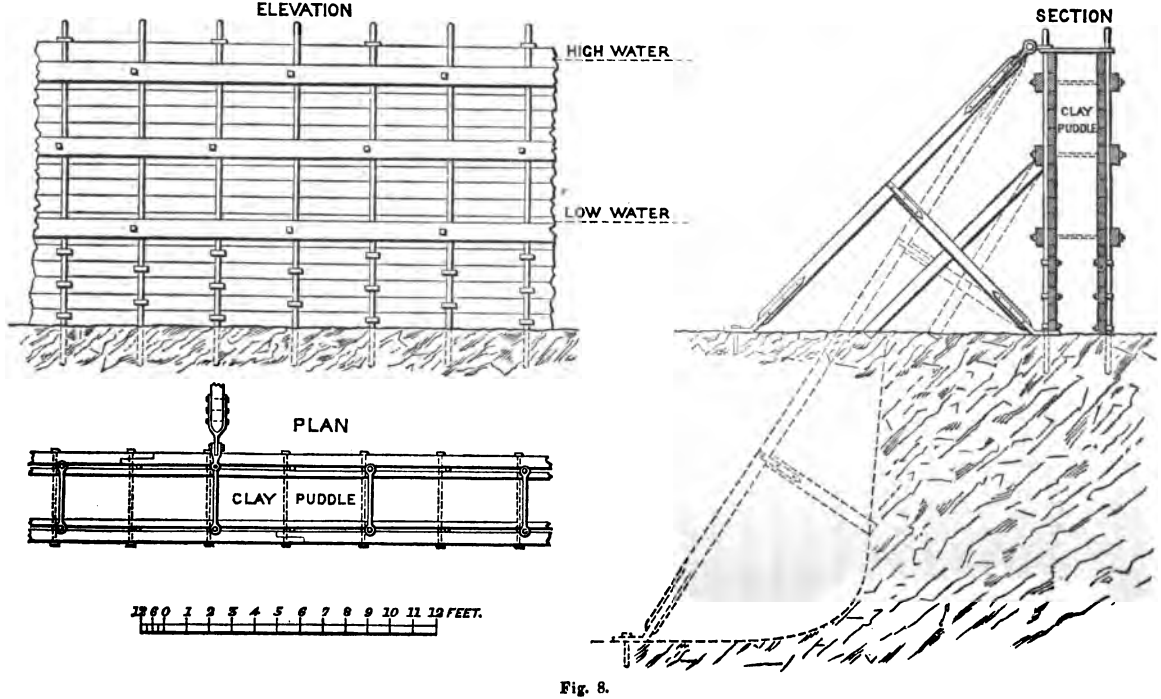


Fig. 8.

5. *River-Walls.*

In open estuaries filled with sand-banks, the courses of rivers are liable to constant alteration, due to every change in the tides or winds. The woodcut (fig. 9) of the River Lune illustrates this remark; the several dotted lines represent the variation of the channel during the period of a few years. This tendency to wander is common to all rivers when left undirected to work their way through a tract of sand; and the evils attending such a state of matters are generally of a serious nature, proceeding mainly from a constant abrasion or wasting of the sand-banks. This abrading action, operating during every flood and ebb tide, sets loose a large amount of floating sand, which is drifted to and fro, and deposited in some new situation. A channel which is constantly shifting its course never remains sufficiently long in one position to form for itself a properly defined bed, but is in fact always in a transition state; the sand which is worn from the *concave* being thrown to the *convex* side of the stream, while some portion of the floating materials, carried to and fro during this process of perpetual change, is often deposited, and forms shoals in the middle of the fairway. A river left in this state of nature cannot possibly attain the *maximum* depth due to the natural scour of the tidal currents, as their power is expended in abrading and removing the sand-banks through which the stream flows, and not, as it ought to be, in deepening and scouring its bed. In such cases what is wanted is to secure a permanent channel, by guiding the first of the flood and the last of the ebb tide by means of walls, so that the strength of the currents may constantly operate on the *same line of channel.* In this way, it is obvious that not only will the advantage of a permanent navigable track

Plan of the River Lune.

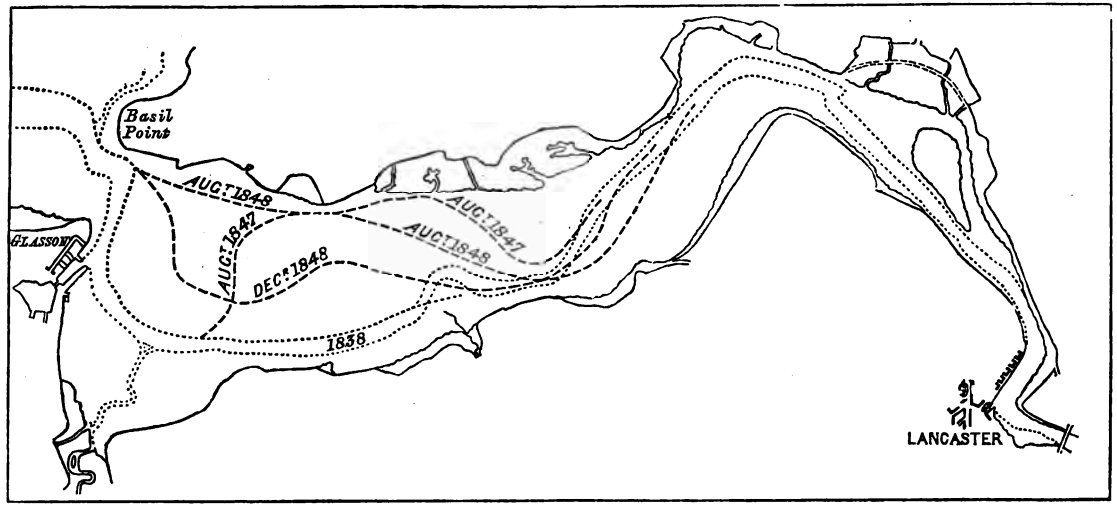


Fig. 9.

be obtained, but the constant action of the currents of flood and ebb tide flowing in the same channel, will secure a much greater permanent depth than they could possibly do if permitted to wander at random through the estuary, sometimes operating in the same channel, and at other times directly opposed to each other.

Comparative advantages of straight and curved walls.

Questions have been raised as to the comparative advantages of straight and curved walls for directing a channel. It is believed that, in most cases, the direction of such walls is necessarily determined, not by any abstract consideration as to the superiority of straight or curved walls, but chiefly by the relative positions of the points between which the stream is to be conducted, and the outline and geological formation of the shores and banks of the estuary that intervene between those points. The consideration of such matters may render it expedient, according to the special circumstances of the locality, to adopt walls having *concave*, *straight*, or *convex* outlines, as shown in figs. 10, 11, and 12.

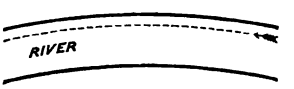


Fig. 10.

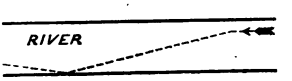


Fig. 11.

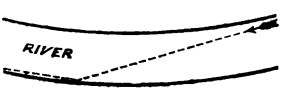


Fig. 12.

Viewed as a purely abstract question, it may, we think, be safely affirmed, that a stream is most likely to follow a

permanent course when directed by a concave wall, as shown in fig. 10, in which the axis of the stream is represented by the dotted line. Dr Young observes that the centrifugal force in curved channels has a tendency to draw the greater portion of the water to the concave side, and thus the greatest scouring power, and consequently the greatest depth of the stream, will be found upon that side. In a channel directed by straight walls (fig. 11), the current has no such decided bias for either wall, and is consequently easily thrown across from side to side. A wall, on the other hand, having a convex outline, as shown in fig. 12, is (especially if the radius of curvature be small) still less suitable as a guide, as the line of wall diverges from the direction of the axis of the current. These remarks are not hypothetical, as the writer has found that their correctness has been verified by cases in actual practice. There is doubtless some disadvantage in the deep water being on one side of the channel, as more particularly shown in the cross section, fig. 13. It would be more convenient for naviga-

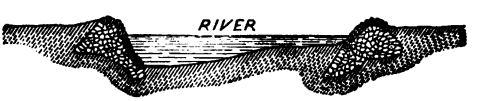


Fig. 13.

tion were the deep water in the centre; but it is found that the current invariably adheres to one or other of the walls, and it is better that the channel should keep constantly to one wall, than that it should alternate from side to side, as is more apt to be the case in absolutely straight channels.

The direction and extent of river-walls must, however, be carefully considered by the engineer with reference to existing circumstances, and every case must be judged *per se*. But we think it will be found safe, in executing such

Section showing disposition of River-Walls in an Estuary.

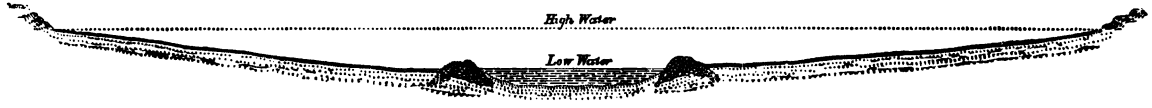


Fig. 14.

works, to adhere as closely as possible to the following general rules :—

First, The channel through open estuaries should, in all cases where funds will admit of it, be guided by double walls. In cases, however, where the estuary is bounded by a hard beach, presenting a favourable line of direction, a single wall may occasionally be found sufficient. All curves which it may be necessary to introduce should be of as large a radius as possible, and should, if practicable, be tangential to each other, or to the straight parts of the line with which they are connected.

Second, The walls should not be *raised* to a higher level above the low-water line than is absolutely necessary for the purpose of conducting the early and late currents of the tide; and their direction should be marked by occasional perches.

Fig. 14 represents the disposition of such walls in estuaries, as executed under the direction of Messrs Stevenson. They are raised from 3 to 5 feet above the low-water line, so that, while they guide the low-water channel, they do not prevent the tide at high-water from flowing on either side of them and filling the estuary.

Third, River-walls should, during their erection, be pushed forward with vigour, and not in a desultory, timid manner; the effect of such a course being to increase the depth of water in which the wall has to be made, and the amount of stone required for its construction.

Fourth, It will be found that such walls as we have been describing will be most advantageously formed of rough rubble stones, backed with clay and gravel, in the manner shown in fig. 15.

It was found by Mr Park, under whose immediate directions, as local engineer, the walls on the River Ribble,

which are about 12 miles in length, were constructed, that their foundations, with few exceptions, did not sink more than a few feet below the sand. He found that it was

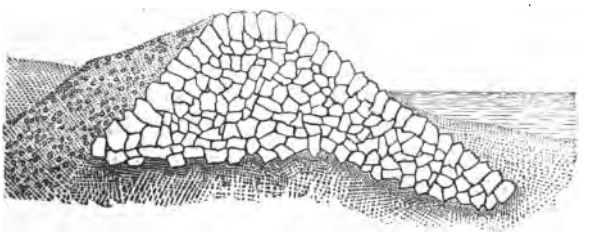


Fig. 15.

advantageous to mix clay in the internal core of the wall; and after the materials were deposited, it was necessary from time to time, in certain places, to add additional stones to make up slips, before attempting to pitch the top or the face of the slope. Walls somewhat similar have also been largely introduced on the Clyde by Mr. Walker.

6. *Scouring.*

The removal of hard portions of the bed of a river by dredging or coffer-dams, and the direction of the channel by low walls, are operations which are in themselves improvements; but they further operate beneficially in causing the currents to scour the softer parts of the river's bed, so that it sometimes happens that by dredging a few hundred yards of hard material from a river's bed, or erecting a short wall, thousands of tons of soft materials are scoured away by the action of the current. In all river improvements this is an effect which should be fully taken into consideration by the engineer, especially in forming estimates; and its importance will be apparent on inspecting the section of the River

Lune (Plate II.) By dredging the upper shoals of that river, which are marked in hatched lines in the section, the whole lower part of the river was deepened by the natural scour, without entailing any expense in its removal. To facilitate this scour, a species of harrow has sometimes been applied, which is drawn to and fro by a tug-steamer across the bank to be removed. This system was extensively employed by Captain Denham in opening the Victoria Channel at the Mersey; it was also employed by Messrs Stevenson at the Tay; but it is obvious that it can only be advantageously used where there is deep water in the immediate neighbourhood of the bank to be removed, in which the sand and mud disturbed by the harrow, and carried off by the current, may be deposited. The process of scouring has, in some situations, to the knowledge of the writer, continued in operation for many years after the completion of the original work, the low-water level of the river continuing gradually to sink; and as this process goes on, it sometimes happens that hard portions of the bottom originally covered become gradually exposed.[1] Such obstructions are, in fact, hard portions of the bed brought to light, in consequence of the improvement of the river, and must not be mistaken for accumulations due to ill-regulated currents. It is necessary, however, that such hard portions should be removed as soon as they appear, otherwise they disturb the currents and occasion shoals. Whenever the depth due to the currents acting in their improved direction has been

[1] Mr Rendel, in his address as president of the Institution of Civil Engineers in 1852, says,—"At the present moment changes are taking place in the Thames and most of the principal rivers, which afford invaluable opportunity for observations on the effects rivers can produce by their own action, and also on what is done by the passage of steam-vessels in keeping the lighter silt constantly in motion."

reached, such obstructions will cease to present themselves.[1]

The effect of works executed according to the principles indicated is,—*First*, to fix the navigable track in a defined course; *second*, to deepen the bed of the river; *third*, to reduce the slope, and lower the low-water level; and, *fourth*, to increase the duration of tidal influence and the quantity of tidal water in the river. The benefits to navigation are threefold:—*First*, greater depth of water; *second*, a properly defined channel; and, *third*, a greater length of time during which, in consequence of the presence of the tide, the river is navigable.

The writer has, before leaving this part of the subject, to state that the works specified are believed to be those most *generally* applicable. All of them may not be applicable in every case; and there may be special cases which render it expedient to adopt works of a somewhat different, and, in some respects, apparently antagonistic character,—such, for example, as the contraction of channels by means of quay-walls.

[1] Admiral Beechey, in his *Observations on the Tides of the River Severn*, mentions a fact which it is proper to record. He says, "While upon the subject of the low-water line, it may here be remarked, that the inverse of the ordinary effect of the spring-tide occurs in the river above Lidney. From Lidney downwards to the sea, the low-water at springs follows the general rule of being lower at such times than at the neaps; but above Lidney the reverse takes place, the low-water at the springs being higher than at the neaps. This, no doubt, is occasioned by the tide at springs throwing more water into the river than can escape before the return of the following tide."

SECTION V.

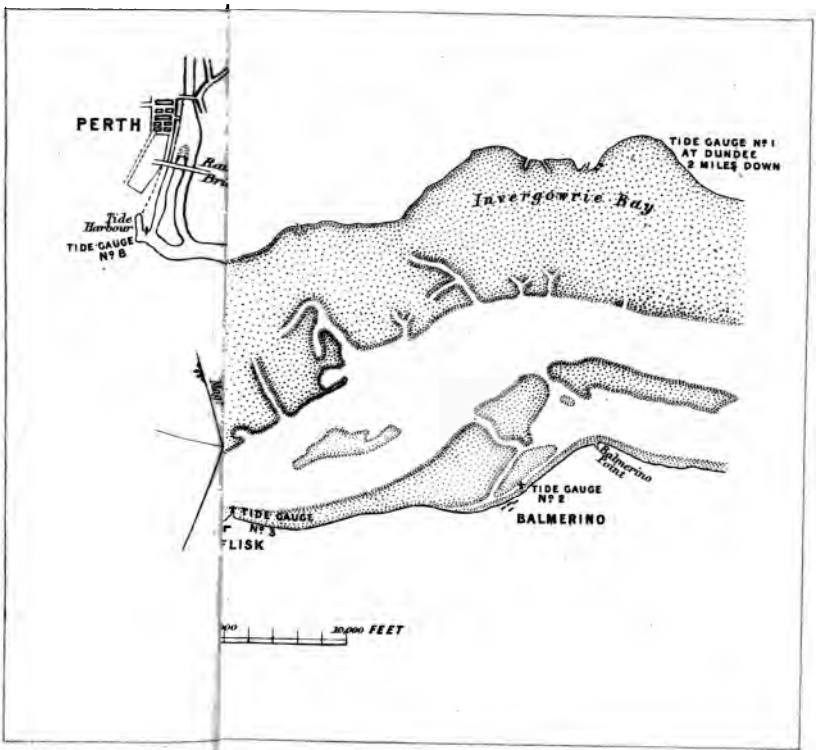
APPLICATION OF THESE WORKS IN PRACTICE.

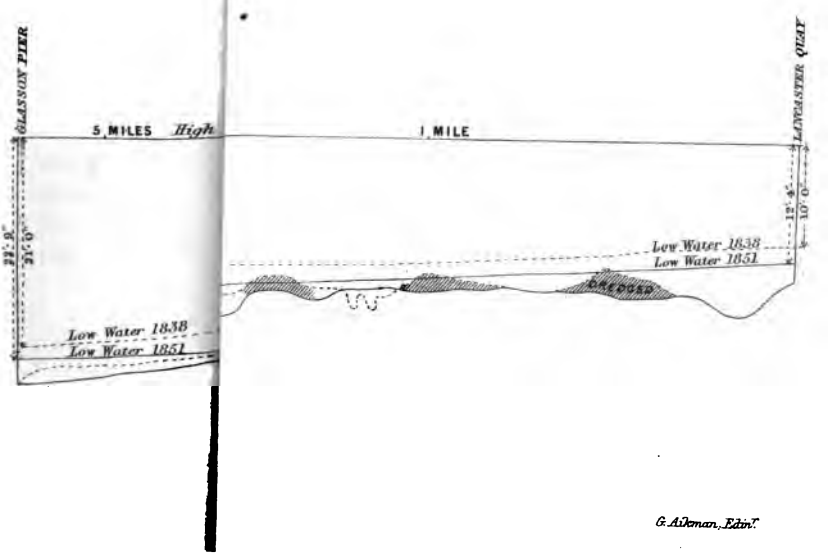
Application of these works in practice.

We come now to give a sketch of navigation improvements, executed in accordance with these general views, and to show their application in practice, and the effect produced by them. The first example to which we shall allude is the River Tay, improved under the advice and direction of Messrs Stevenson of Edinburgh; as we know of no instance in which the improvements effected by particular works are more fully and satisfactorily demonstrated by a comparison of observations made *previously* and *subsequently* to their execution, than in the case of that navigation; where the changes were brought about in so short a time, and were so marked as to leave no doubt, even to superficial observers, of their attainment, and no difficulty, by the use of proper means, in ascertaining their amount.

River Tay.

The River Tay, with its numerous tributaries, as stated in the table at the end of this treatise, receives the drainage-water of a district of Scotland amounting to 2283 square miles, as measured on Arrowsmith's Map. Its *mean* discharge has been ascertained to be 274,000 cubic feet, or 7645 tons of water per minute. It is navigable as far as Perth, which is 22 miles from Dundee, and 32 from the German Ocean. The different points on the river, hereafter to be referred to, will be seen in the small chart given in Plate II.; and we propose, in this particular case, to enter somewhat into detail as to the nature of the obstructions to the





G. Aikman, Edin.r

navigation, the means employed for their removal, and the effects produced by the works on the tidal currents; as the remarks made will, it is believed, serve to illustrate the subject of river improvement generally.

Before the commencement of the works, certain ridges, called "fords," stretched across the bed of the river at different points between Perth and Newburgh, and obstructed the passage to such a degree, that vessels drawing from 10 to 11 feet could not, during the highest tides, make their way up to Perth without great difficulty. The depth of water on these fords, the most objectionable of which were six in number, varied from 1 foot 9 inches to 2 feet 6 inches at low, and 11 feet 9 inches to 14 feet at high water of spring tides; so that the regulating navigable depth, under the most favourable circumstances, could not be reckoned at more than 11 feet. In addition to the shallowness of the water, many detached boulder stones lay scattered over the bottom. Numerous "fishing cairns," or collections of stones and gravel, had also been laid down, without regard to any object but the special one in which the salmon-fishers were interested, and in many cases they formed very prominent and dangerous obstructions to vessels. The chief disadvantages experienced by vessels in the unimproved state of the river was the risk of their being detained by grounding, or being otherwise obstructed at these defective places, so as to lose the tide at Perth,—a misfortune which, at times when the tides were falling from springs to neaps, often led to the necessity either of lightening the vessel, or of detaining her till the succeeding springs afforded sufficient depth for passing the fords. The great object aimed at, therefore, was to remove every cause of detention, and facilitate the propagation of the tidal wave in the upper part of the river, so that inward-bound vessels might take

the first of the flood to enable them to reach Perth in one tide. Nor was it, indeed, less important to remove every obstacle that might prevent outward-bound vessels from reaching Newburgh, and the more open and deep parts of the navigation, before low-water of the tide with which they left Perth.

The works undertaken by the harbour commissioners of Perth for the purpose of remedying the evils alluded to, and which extended over six working seasons, may be briefly described as follows :—

1*st*. The fords, and many intermediate shallows, were deepened by steam-dredging; and the system of harrowing was employed in some of the softer banks in the lower part of the river. The large detached boulders and "fishing cairns," which obstructed the passage of vessels, were also removed.

2*d*. Three subsidiary channels, or offshoots from the main stream, at Sleepless, Darry, and Balhepburn islands, the positions of which will be seen on the plan, were shut up by embankments formed of the produce of the dredging, so as to confine the whole of the water to the navigable channel.

3*d*. In some places the banks on either side of the river beyond low-water mark, where much contracted, were excavated, in order to equalize the currents, by allowing sufficient space for the free passage of the water; and this was more especially done on the shores opposite Sleepless and Darry islands, where the shutting up of the secondary channels rendered it more necessary.

The benefit to the navigation in consequence of the completion of these works has been of a twofold kind; for not only has the depth of water been materially increased by actual deepening of the water-way, and the removal of numerous obstructions from the bed of the river, but a

clearer and freer passage has been made for the flow of the tide, which now begins to rise at Perth much sooner than before; and as the time of high-water is unaltered, the advantages of increased depth due to the presence of the tide is proportionally increased throughout the whole range of the navigation; or, in other words, the duration of tidal influence has been prolonged.

The depths at the shallowest places are now pretty nearly equalized, being 5 feet at low and 15 feet at high water, of ordinary spring tides, instead, as formerly, of 1 foot 9 inches at low and 11 feet at high water. Steamers of small draught of water can now therefore ply at *low-water*, and vessels drawing 14 feet can now come up to Perth in *one tide* with ease and safety.

In obtaining the requisite data, both as to the design and execution of these works, minute tidal observations were made at various times during a period of ten years, from 1833 to 1844 inclusive, throughout the River and Firth of Tay, at the following stations,—viz., Dundee, which is marked No. 1 on the plan, Plate II.; Balmerino, No. 2; Flisk Point, No. 3; Balmbreich Castle, No. 4; Newburgh, No. 5; Carpow, No. 6; Kinfauns, No. 7; and Perth tide harbour, No. 8. The general results deduced from these observations are given in the following tables, and show, by the favourable change which has been effected in the tidal phenomena of the estuary, that the works executed fully answered the intended end:—

1. *Propagation of Tidal Wave.*

The following table of elapsed times, between arrival of the tide-wave, or commencement of the tidal flow, at the following stations, during *spring* tides in 1833 and 1834, shows the rate of its propagation:—

	Time. H. M.	Distance in Miles.	Rate of Tide-Wave in Miles per Hour.
Dundee to Balmerino.....	0 16	5·00	18·75
Balmerino to Flisk Point.....	0 29	2·93	6·06
Flisk Point to Balmbreich.....	0 26	2·04	4·69
Balmbreich to Newburgh.....	0 53	3·42	3·86
Newburgh to Perth (tide harbour).....	2 30	8·56	3·42

The result of observations made in 1842, 1843, and 1844, on spring tides, give the same velocity, as above stated, between Dundee and Newburgh, and the following rates between Newburgh and Perth:—

	Time. H. M.	Distance in Miles.	Rate of Tide-Wave in Miles per Hour.
Newburgh to Carpow.....	0 25	1·33	3·17
Carpow to Kinfauns.....	0 55	4·92	5·36
Kinfauns to Perth (tide har.)..	0 20	2·32	6·93
Giving, as a mean for the whole distance from Newburgh to Perth in 1844...	1 40	8·56	5·13
Time from Newburgh to Perth in 1833..	2 30	8·56	3·42

Thus showing an increase in the velocity of the tide-wave in the upper part of the river, which was improved, of more than 1⅔ mile per hour as the result of the improvements.

The difference of the time in *neap* tides between Newburgh and Perth in 1844, was 1 h. 53 m.

2. *High-Water Level.*

The levels of the surface of high-water at different stations throughout the river have been found to be unchanged, and the following results refer to the years 1833 and 1844:—

From Flisk Point to Balmbreich there is a fall of	5 in.	Spring Tides.
... Balmbreich to Newburgh there is a rise of	7½ „	
... Newburgh to Perth (tide harbour) there is a rise of.....	18 „	

From Flisk to Balmbreich there is a fall of....	2½ in.	Neap Tides.
... Balmbreich to Newburgh there is a rise of	6 „	
... Newburgh to Perth (tide harbour) there is a rise of	12 „	

3. *Low-Water Level.*

Rise on the Surface of Low-water (Spring Tides) in 1833.

	Ft. in.	Distance in Miles.	Rate of Slope per Mile in Inches.	Rate of Tide in Miles per Hour.
Flisk to Balmbreich there was a rise of.....	0 4	2·04	1·95	4·69
Balmbreich to Newburgh, a rise of.....	2 8	3·42	9·35	3·86
Newburgh to Perth (tide harbour), a rise of.....	4 0	8·56	5·06	3·42

Rise on the Low-water of Spring Tides in 1844.

Newburgh to Carpow, there is a rise of.....	0 5	1·33	3·75	3·17
Carpow to Perth there is a rise of.....	1 7	7·23	2·63	...
Hence from Newburgh to Perth, 1844, the rise is..	2 0	8·56	2·80	5·13

The result of the observations of 1844 thus gives a depression on the level of the low-water mark of two feet at Perth tide harbour.

4. *Duration of Flood and Ebb.*

The results of observations in 1833 and 1844 at Newburgh show that the durations of flood and ebb tides at that place are unchanged. The times are as follows:—

	H.	M.
Spring Tides flow.....	4	20
... ebb.....	7	20

	H.	M.
Neap Tides flow	4	30
... ebb	6	45
At Perth in 1833:—		
Spring Tides flowed	2	20
... ebbed	7	0
Neap Tides flowed	3	15
... ebbed	7	0
At Perth in 1844:—		
Spring Tides flowed	3	10
... ebbed	7	0
Neap Tides flowed	3	10
... ebbed	7	0
Increase of duration of Flood in springs at Perth	0	50

It will be observed from these tables that important changes have taken place:—

First, The fall on the surface of the river from the tide basin at Perth to Newburgh in the year 1833 was 4 *feet*, but after the works were executed it was only 2 *feet*.

Second, In 1833 the passage of the tidal wave from Newburgh to Perth (8·56 miles) occupied 2 hours 30 minutes, being at the rate of 3·42 miles per hour; but it is now propagated between the same places in 1 hour 40 minutes, being at the rate of 5·13 miles per hour,—giving a *decrease* in the time of 50 minutes, and an *increase* in the speed of the first wave of flood of more than 1½ mile per hour, since the commencement of the works.

Third, The spring tides in 1833 at Perth flowed 2 hours 20 minutes, and ebbed 7 hours; but now the tide flows 3 hours 10 minutes, and ebbs 7 hours,—being an *increase* in the duration of flood of 50 minutes.

River Forth.

The works on the Forth, also executed under the direction of Messrs Stevenson, produced changes on the tidal phenomena, which, in connection with those described on the Tay, are interesting and instructive as regards the pro-

Section of River Forth.

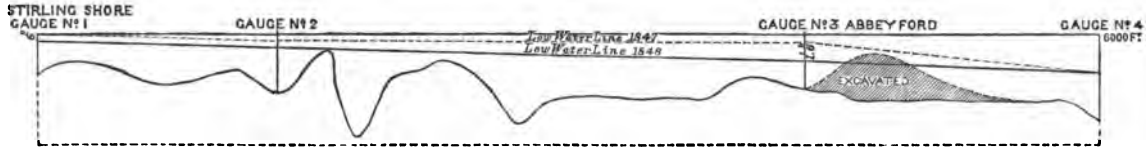


Fig. 16.

pagation of the tide, and therefore we shall briefly allude to them. The river between Stirling and Alloa is very circuitous, the distance by the navigation being 10½ miles, while in the direct line it measures only 5 miles. The navigation was found to be impeded by seven fords or shallows which occur between Alloa and Stirling, and are composed of boulder stones, varying from a few pounds to several tons in weight, embedded in clay.

It was determined, in the first instance, to remove two of these obstructions, viz., the "Town" and the "Abbey" fords, which lie nearest to Stirling, and having the smallest depth of water, form the greatest obstruction to the free passage of vessels. The works were commenced at the lower end of the Abbey ford, and were carried regularly upwards. The new channel excavated through this ford was about 500 yards in length and 75 feet in breadth, and was deepened in some places about 3 feet 6 inches.

Previous to the commencement of the work, tide-gauges were erected in the positions marked 1, 2, 3, and 4, in fig. 16, on which a series of observations was made for the purpose of establishing the original tidal phenomena of the river. After the Abbey ford was cut through, farther observations were made on the same gauges; and it is to a comparison of these two sets of observations that we desire specially to refer. It is necessary to explain that gauge No. 1 is at Stirling quay, No. 2 about 500 yards farther down, No. 3 at the top of the Abbey ford, and No. 4 immediately below it. It will therefore be understood that the Abbey ford, through which a channel was cut, lies between gauges Nos. 3 and 4. The whole of the gauges were placed on the same level, so that their *readings* might be more easily compared; and the following are the results

obtained with reference to the level of the low-water line:—

Levels of Low-water Line.	Gauge No. 4.	Gauge No. 3.	Gauge No. 2.	Gauge No. 1.
In 1847 the low-water line was found to stand at the following levels	Ft. in.	Ft. in.	Ft. in.	Ft. in.
	2 0	5 0	5 3	5 6
In 1840	2 0	3 6	4 6	5 0
Depression	0 0	1 6	0 9	0 6

From this tabular statement, we find that the low-water line at No. 4, which is below the site of the works, remains unaltered, but that it has fallen 1 foot 6 in. at the top of the Abbey ford (through which the cut has been made). It further appears that the formation of this cut has drained off the water, and lowered the surface 9 inches at gauge No. 2, and 6 inches at gauge No. 1, which is at Stirling. The former and present low-water lines and bed of the river are represented in fig. 16, in which is also shown the amount of excavation on the Abbey Ford by hatched lines. This general depression of the river has of course altered the slopes or inclinations formed by the surface of low-water; the slope between 4 and 3 being decreased, while the inclinations between 3 and 2, and between 2 and 1, have been increased in the following ratios:—

Inclinations.	Dist.	1847.	1848.	Difference in 1848.
	Feet.	Inches per Mile.	Inches per Mile.	
Inclination between 4 and 3	1550	122·5	61·3	−61·2
Do. do. 3 and 2	3050	5·19	20·77	+15·58
Do. do. 2 and 1	1400	11·31	22·62	+11·31

Again, these changes on the low-water line have pro-

duced corresponding alterations on the velocities of the first wave of flood, which are found to be as follows:—

Velocities.	1847.	1848.	Difference.
	Minutes.	Minutes.	Minutes.
Time occupied by first wave of tide in passing between gauges Nos. 4 and 3	24	8	−16
Do. do. Nos. 3 and 2...	6	11½	+ 5½
Do. do. Nos. 2 and 1...	6	8½	+ 2½
Do. do. Nos. 4 and 1...	36	28	− 8

From this it appears that between Nos. 4 and 3 there is an acceleration of 16 minutes, while between 3 and 1 there is a retardation of 8 minutes, leaving the difference, or 8 minutes, as the actual amount of acceleration at Stirling, due to the removal of the ford and the lowering of the low-water level 6 inches at that place. The rates of propagation in miles per hour are as follows:—

Rates of Propagation.	1847.	1848.	Difference.
	Miles per hour.	Miles per hour.	
Rates of propagation between Nos. 4 and 3.....	·65	2·2	+1·55
Do. do. Nos. 3 and 2...	5·77	3·0	−2·77
Do. do. Nos. 2 and 1...	2·65	1·87	−0·78

Relations of the slopes and rates of tidal propagation.

These observations and results seem to throw some additional light on the circumstances which modify the propagation of the tidal wave. The table of the results obtained at the Tay shows that the *de*creased inclination of the low-water lines of that river was attended by an *acceleration* of the velocity of the tidal wave; and the above observations further show that a *retardation* has attended an *in*creased inclination of the low-water line of the upper part of the

Forth. From the foregoing tabular statements, it will be seen that between gauges 4 and 3, where the slope has been decreased, the propagation has been accelerated; while between 3 and 2, where, from the state of the works when the observations were made, it is found to have been increased, the rate of propagation had been sensibly retarded. It is worthy of remark, however, that the rates of propagation do not, either at the Tay or Forth, *bear any constant relation to the slopes*, but are modified by other circumstances; in proof of which, it will be found that the rate of propagation at the Forth between gauges 4 and 3, where the slope is 61·3 inches per mile, is actually greater than between gauges 2 and 1, where it is only 22·62 inches per mile. The circumstances of the Forth at this particular place are somewhat peculiar. Before the Abbey ford was cut through, it acted as a dam extending across the river, and had the effect of increasing the depth at low-water all the way up to Stirling. By cutting the channel through the ford, however, not only has the water been drained off and rendered shallow, but its surface has been broken by the projection of boulders from the bottom, which formerly were entirely covered; and while this effect has taken place in the upper part of the river, a comparatively smooth cut, with regular sides and bottom, has been formed in the Abbey ford, through which the river flows at low-water in a body of considerable depth. The writer therefore attributes the slow propagation of the tide between 2 and 1 to the shallowness of the water and the very rugged state of the bottom, which is in many places completely studded with boulders, rising some above the surface at low-water, and others to within a few inches of it; while the high velocity up the steep slope of the ford is to be attributed—1*st*, To the depth of water caused by the whole river being made to pass

through a comparatively narrow channel; 2*d*, To the rectangular cross section of the cut; and 3*d*, To the smoothness of the sides and bottom. At the Firth of Dornoch, again, as already noticed, between the Quarry and Bonar Bridge, a distance of 1 mile, although the water is shallow and the bottom rough, it is not, on the whole, more so than between gauges 1 and 2 on the Forth; but at the Dornoch the slope on that mile is no less than 6 feet 6 inches, and the rate of propagation is only two-thirds of a mile per hour. Moreover, it was found that the tide did not begin to show at Bonar until it had risen 6 feet 6 inches on the gauge at the Quarry, being the exact difference of level between the two points of observation.

Laws of tidal propagation in rivers.

These various results as to slopes and rates of propagation, as well as others which have come under the writer's notice, seem to justify the following deductions as to the propagation of the tide-wave in rivers with sloping surfaces and irregular bottoms:—1*st*, That a decrease of slope is followed by an acceleration of the rate of propagation of the tidal wave. 2*d*, That an increase of slope is followed by a retardation of the rate of propagation. 3*d*, That the rate of propagation does not bear any constant relation to the amount of slope, although it is to some extent modified by it. 4*th*, That while the rate of propagation in rivers is in some measure due to the depth of water, it is nevertheless influenced by the slope of the surface, the form of the channel, and the obstructions protruding from the sides or bottom. 5*th*, That if not in all cases, at least when there are steep slopes and shallow water, as at the Dornoch Firth, the level of the crest of the wave must rise to the level of the surface of the water (or perhaps the bed of the river) above it, before a progressive motion takes place; and, 6*th*, That, from the difficulty of dealing with so many variable

elements, it is impossible in most rivers to determine the ruling circumstances which can be held as regulating the rate of tidal propagation.

The Clyde affords a striking proof of the extent to which river improvements may be carried. So insignificant was the stream in its natural state, that Smeaton, in 1775, proposed to erect a dam with locks in the lower part of the river, and to convert it into a tidal canal. In 1775, however, Golburne surveyed the river, and although he found that as far down as Kilpatrick the depth of water was only 2 feet, he nevertheless recommended the construction of a series of jetties from either side, for the purpose of narrowing and deepening the stream; and this may be held as the commencement of the improvement of the River Clyde, which originally barely afforded depth of water for larger craft than flat boats, but which now, as our readers know, admits vessels of large draught up to Glasgow Bridge. The reader must be cautioned from supposing, however, that this result has been attained by means of the jetties which were erected under the advice of Golburne. It was soon discovered that the object could not be gained by such works. It was not until the ends of the jetties were connected by longitudinal walls, and until dredging-machines were extensively employed, that the Clyde improvements began to assume an importance commensurate with the vast commercial interests of the city of Glasgow and surrounding districts. The works on the Clyde have latterly been under the direction of Mr Walker, and have mainly consisted in dredging, forming longitudinal walls, and increasing the width of certain parts of the channel, which had in the early stage of the improvements been contracted to an injurious extent. River Clyde.

The Ribble in Lancashire, the improvements of which River Ribble.

were designed by Messrs Stevenson, presents an example of a great amount of additional depth having been obtained in a comparatively short space of time. That river, according to Mr Park, who conducted, as resident engineer, the greater part of the works, has a course of 82 miles, and drains 900 square miles of the counties of York and Lancaster. The formation of the bed in which it flows rendered the state of the tidal compartment previous to the improvements very defective. The bottom in the lower part of the river consists of loose sand; while that of the upper reach is alternately compact gravel and sandstone rock. About half a mile below Preston, in particular, it was found that a solid ridge of sandstone, extending to 300 yards in length, stretched quite across the channel. Its surface was from 3 to 5 feet higher than the general bed of the river both above and below it, and so prominent an obstruction did it form, that the higher parts of the rock were occasionally left dry during the long droughts of summer. The propagation of the tidal wave, and free flow of the currents, were checked on approaching it; while the power of the tidal and fresh-water scours was in a great measure neutralized and rendered almost unavailable in keeping open the upper and lower stretches of the navigation; so that its influence in obstructing the river resembled that of a great artificial weir stretching across the stream. In proof of this, it may be stated that the ordinary rise of spring tides at Lytham, which is 12 miles seaward of Preston, is about 19 feet,[1] and that of neap tides is 14 feet, while at Preston, prior to the operations, the rise of spring-tides did not exceed 6 feet, and neap tides of 13 or 14 feet

[1] Captain Sir Edward Belcher, while engaged in making the Admiralty survey of the Ribble, found that on one occasion the tide at Lytham rose 25 feet 7½ inches.

rise at Lytham did not reach Preston at all. The removal of the rock which encumbered the bed, was naturally viewed as the most urgent and important work for effecting an improvement in the tidal phenomena and general depth of water. To this, therefore, the Navigation Company first directed its attention, and in the course of eighteen months, succeeded in excavating a channel through the solid rock 300 yards in length, and in some places 13 feet 6 inches in depth. This operation was successfully accomplished, at an expense not exceeding L.10,000, by means of a coffer-dam of the construction already shown in fig. 8. In addition to this work, about 480,000 tons of gravel and sand have been removed from the upper part of the river by dredging; and 9 miles of low rubble walling (formed, in so far as it was available for the purpose, of the rock excavated from the bed of the river) have been constructed in accordance with the sketch shown in fig. 15, for guiding the current in the lower channel.

The effect of the different works that have been executed has been to increase the tidal range at Preston about 5 feet, and to accelerate the propagation of the tidal wave nearly an hour; and vessels, to which the navigation may be said to have been previously closed, now come up to the quays of Preston with comparative ease and safety.

River Lune.

The works on the Lune in Lancashire were executed by Messrs Stevenson, under the direction of the Admiralty. They extended over a period of four years, and consisted in removing fords by dredging, shutting up subsidiary channels, and erecting river walls; the whole operation costing under L.10,000. The sketch of the Lune in fig. 9 shows the varying state of the channel in its original condition, which was regulated by means of a single rubble wall, as the funds did not admit of a double wall being erected.

It was necessary also, from the configuration of the shores, that the channel should follow the convex side of the wall which should, if possible, be avoided, as some difficulty occurs in maintaining the channel always close to the wall, —a difficulty which can only be removed by the formation of a second wall; and we mention this as an example of the desirableness, as already stated, of forming double walls in all cases when the funds at disposal will admit of it. Fig. 17 represents the gradual depression of the tidal lines

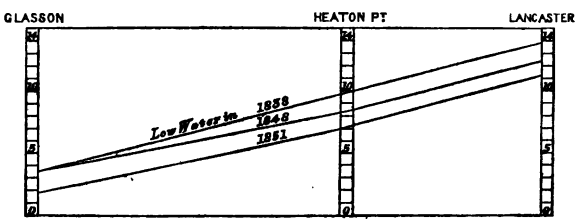


Fig. 17.

since the works commenced: the upper line shows the surface of the river in 1838, the intermediate line in 1848, and the lower line in 1851. The effect of the works has been to increase the depth of water up to the quays at Lancaster about 4 feet, and to prolong the duration of the tidal influence at that place thirty minutes in neap, and one hour and a half in spring tides; so that vessels can approach and leave Lancaster much earlier than formerly, while the improved channel is navigated with much greater ease.

It is unnecessary to give farther examples of navigations which have been benefited by means of works constructed on the principles which we have indicated. We doubt not that other cases could be quoted, although we do not possess sufficient details to enable us to do so; and we close this part of our subject by stating that the further extension of these

works in such rivers as the Tay, the Ribble, or the Lune, and their application in many other cases, would be followed by a greatly increased improvement of their navigation.

Instances might be referred to where a course of treatment opposed to that which we have recommended has not been followed by similar favourable results; but we deem it sufficient to confine this treatise to an exposition of the correct principles of river improvement, without discussing erroneous practice or its baneful results; the more so as these have been most fully and ably treated by Mr E. K. Calver, R.N., whose investigations into the former and present state of some of our tidal rivers are of great value to the hydraulic engineer.[1]

[1] *The Conservation and Improvement of Tidal Rivers*, by E. K. Calver, R.N., London, Weale, 1863.

SECTION VI.

SITUATIONS WHERE THE PRINCIPLES OF IMPROVEMENT RECOMMENDED ARE NOT APPLICABLE.

We have further to state, that in some situations the principles of improvement which we have advanced will be found to be of very limited application. Such cases indeed are rarely to be met with, but still it is necessary to notice them. We allude to rivers where the tidal or intermediate compartments are, from natural causes, of very small extent.

The Erne. In illustration of what we mean, we may refer to the Erne in Donegal, which has a tidal capacity of only $2\frac{3}{4}$ miles, extending from the bar up to the town of Ballyshannon, where the tidal flow is terminated by the "Salmon Leap," a perpendicular rise in the bed of the river of about 15 feet in height. This waterfall forms the limit of the tidal flow, beyond which it could not, without works of a gigantic character, be extended.

The Ness. Another case is the Ness, which has a short course of about 2 miles, from a little above the town of Inverness to the Beauly Firth, at Kessock Roads. The difficulties attending the navigation of this river are mainly the prevailing outward currents due to the physical conformation of the bed of the Ness, which may be shortly described, as it illustrates generally a class of rivers which are very difficult to improve:—1*st*, The rise of ordinary spring tides at the mouth of the river is 14 feet. 2*d*, The dsitance to which the influence of such tides extends is only about 2 miles, which includes the whole tidal com-

partment of the river. 3*d*, The slope or inclination of the low-water line of this tidal compartment is no less than 7 feet per mile, and the tide takes from two to three hours to make its way up the first mile. 4*th*, The natural result of such a state of matters is, that no tidal current is generated at the mouth and propagated up the stream, and consequently the phenomenon of a current due to flood-tide may be said to be almost unknown.

Under these circumstances, the barrier to the free navigation of the River Ness is the absence of a tidal current or in-draught, to aid the entrance of vessels from Kessock Roads, and assist their progress up to the quays. This is at present effected by help of men and horses against the nearly constant downward current, which varies in strength with the amount of water discharged by the River Ness, during its frequent heavy floods.[1]

Back-water.

This absence of sufficient internal capacity and gentleness of inclination to admit of the generation of tidal currents is strikingly exemplified in the two rivers to which we have alluded, and naturally leads us to offer some general remarks in passing on the subject of the "backwater" and the "slopes" of rivers. In most, if not in all cases, it will be found (as more particularly noticed hereafter in section 8, in treating of bars) that it is of the highest importance to maintain unimpaired the full tidal capacity, and to be careful to make no reduction of its amount without obtaining an enlargement of the low-water section, to compensate for any reduction which it may be found advisable to make at or near the high-water line.

The subject of the reduction of backwater has given rise

[1] See Report of Tidal Harbour Commission, by D. Stevenson, C.E., and Joseph Maynard, R.N., in *Admiralty Reports* for 9th March, 1847.

to various questions, which have occupied the attention of the engineer; but as every case must be judged on its own merits, and no two situations are exactly alike, it would be unprofitable to enter upon the discussion of the various arguments that have been adduced with reference to particular localities. All we can do is to lay down the general principle, that the more the tidal influence can be extended, and the larger the amount of backwater that can be obtained, the greater will be the benefit conferred on the navigation from the bar upwards; provided always that such increased scouring power is, by judicious works, placed under proper regulation. The question as to the possibility of excluding the tide from any part of an estuary, without injury to the outer channels, is a wide subject, as will be seen from our merely stating some of the considerations which may be held to determine the peculiar circumstances in which the exclusion of water may be compensated. These are, the configuration of the banks and bed of the estuary, the simultaneous levels of the surface of the water at different periods of the tide throughout the estuary, the velocities of the surface and under-currents at different periods of tide, and the times of ebbing and flowing, together with many other more minute data *peculiar to each case*, which it is not possible to specify in a general summary.

Slopes of rivers.

The existence of a moderate amount of fall or slope on the low-water line of a river is a hopeful feature in its capabilities for improvement; while on the other hand, such a slope as that on the Ness proves a great barrier to its extended improvement as a tidal river; for it is obvious, that to obtain on that river a slope sufficiently gentle for easy navigation, it would be necessary to lower its bed to so great an extent, and to execute works of such magnitude, as to render it inexpedient to entertain such a project.

The consideration of the proper slope is important in river engineering. Dubuat considers 1 in 500,000 to be the smallest possible inclination that can be given to a canal to produce sensible motion. It will be found, on inspecting the table at the end of this treatise, that the slopes of tidal rivers vary from a few inches to several feet per mile.[1] As a general rule, we should say that the engineer may calculate on reducing the slopes of tidal navigations to 4 inches per mile $= \frac{1}{15840}$; and that they should not, if possible, exceed 10 inches per mile $= \frac{1}{6336}$.

Directly connected with the slope is the velocity of a stream, —an important matter as affecting navigation, for it cannot be conducted with advantage in situations where the velocity of the currents is very great. The velocities of tidal currents in some places are very great; as, for example, in the Pentland Firth, where Captain Otter measured a velocity of 10·8 miles per hour, and in the Severn, where it was found to be 9 miles per hour. From 2 to 3 miles per hour is, however, a very common velocity on many of the rivers in this country, and it is found to present no inconvenience to the navigation of vessels. The following are the velocities of the currents in different rivers, with their authorities. The whole of them are surface velocities:— Velocities of river currents.

[1] The slope of the river Niagara at the rapids, immediately above the far-famed "Falls," is said to be 50 feet in half a mile, or 1 in 52·8.

Velocities of the Currents in different Rivers.

Name.	Per Hour.	Authority.	Name.	Per Hour.	Authority.
	Mls. yds.			Miles.	
Mississippi	5 0	Ellet.	Severn, near Stonebench, ebb	3·12	Admiral Beechey.
Clyde, between Glasgow and junction of Cart, during ebb	0 1576	W. Bald.	Wear, spring tide, ebb	1½ to 2½	J. Murray, C.E.
			Do., neap tides, ,,	1 to 1¾	Do.
Do., flood	0 771	Do.	Do., flood tides	1 to 2	Do.
Do., from junction of Cart to Dumbarton, ebb	1 1069	Do.		Knots.	
			Tay at Buddonness, sp. tides	2 to 2½	North Sea Pilot.
Do., flood	0 1561	Do.		Miles.	
Do. during high floods below Glasgow harbour, ebb	2 1613	Do.	Do. at Perth	3·09	Messrs Stevenson.
			Willowgate at Perth	1·55	Do.
Do. at narrow places during floods	3 1148	Do.	Dornoch Firth, Meikleferry, flood	2·63	Do.
			Do. do. ebb	2·55	Do.
Severn, near Stonebench, flood, spring tide	4 950	Admiral Beechey.	Tay at Mugdrum, flood and ebb	2 to 2½	Do.
			Thames	2 to 2¾	G. Rennie.

SECTION VII.

WORKS FOR ACCOMMODATION OF VESSELS.

The works we have described are for facilitating the ingress and egress of vessels. In addition to this, it is necessary to provide for their accommodation. For this purpose it is desirable, where local circumstances admit of it, that it should be possible to withdraw them from the action of the river currents which, during heavy floods accompanied by ice, are often very destructive to shipping.

This is accomplished in a simple manner by forming what are termed tide-basins, which are artificial cuts retiring from the stream having their sides bounded by quays or wharves, into which vessels may be withdrawn, but where they are still liable to take the ground at low-water. The object is accomplished more effectually by means of wet docks, for details of which the reader is referred to the article on that subject. In many situations, however, especially where the river is wide, and affords ample room, as in the case of the Foyle at Londonderry, for example, the berthage for vessels is afforded by means of lines of quays formed along the shore.

Tide-basins.

Docks.

Such quays constitute an important part of all harbours which are formed in tidal rivers; and in illustration of some of the various methods of construction adopted in such cases we submit the following cross sections. Fig. 18 shows the timber wharfage constructed by Mr Smith at Belfast,

River quays or wharves.

which is composed of a facing of timber-work secured by iron ties fixed to piles, the space behind the face-work being filled up, and the roadway formed at the top. Fig. 19 is a plan showing the positions of the piles and ties. Some-

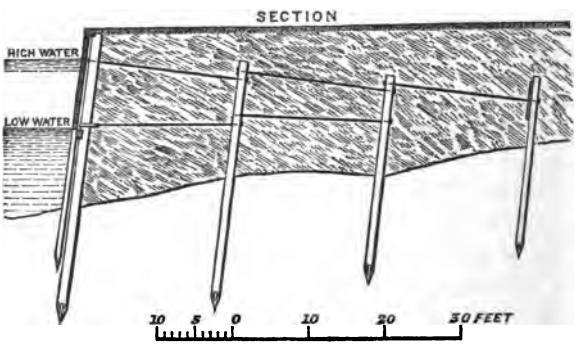


Fig. 18.

times a similar face-work is employed, backed by a wall of concrete; and iron plates have also been used for the facing,

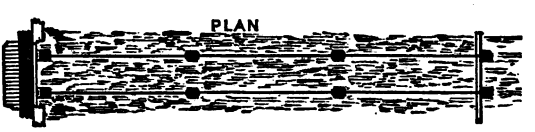
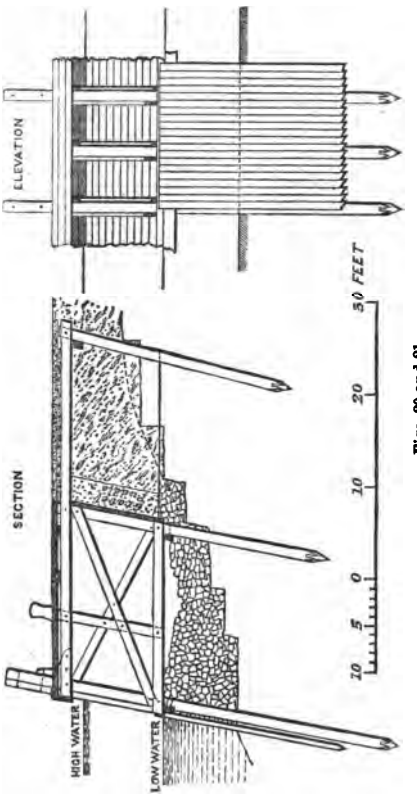


Fig. 19.

instead of planking. Figs. 20 and 21 are a section and elevation of the quays of Londonderry, designed and executed by Messrs Stevenson. At this place the ground is very soft, and in order as much as possible to reduce the weight, the

Quays at Londonderry.



Figs. 20 and 21.

front compartment of the wharf next the river is left open. Figs. 22 and 23, again, are sections of the stone wharves now being constructed from a design by Mr Walker, at Glasgow, under the superintendence of Mr Ure. Fig. 22 is the section adapted to a clay bottom; and fig. 23 is that which is adopted when the bottom consists of sand. In both cases the depth of water in front of the quays is 20 feet at

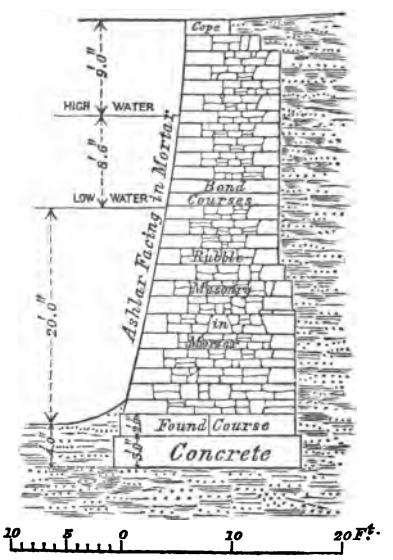


Fig. 22.

low-water, and is intended to accommodate merchant vessels of the largest class.

These examples furnish an illustration of the means employed for providing wharfage on tidal rivers; the details of their construction must be studied in treatises on such

branches of engineering construction as Carpentry, Masonry, Piling, Foundations, Mortar, and Quay Walls.

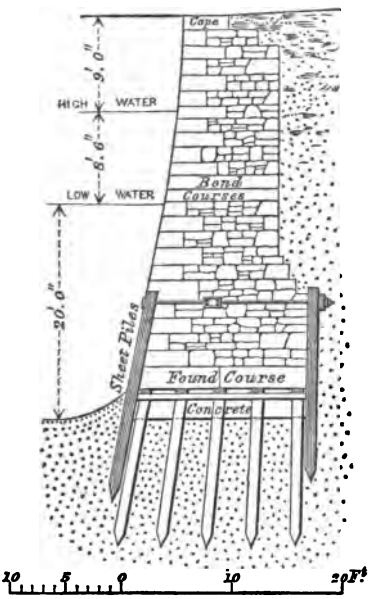


Fig. 23.

Swing-bridges.

The engineer is often called on to construct swing-bridges in connection with navigations, but for particulars as to such works, reference is made to the article IRON BRIDGES in vol. xii. of the Eighth Edition of the *Encyclopædia Britannica*.

SECTION VIII.

"SEA PROPER" DEPARTMENT OF RIVERS.

Having considered the treatment of rivers from their source to the ocean embracing the upper or "river proper," and the intermediate or "tidal compartment," we have now to direct attention to what we have termed the "sea proper" compartment, which, in the sense we have attached to it, may be said to embrace the phenomena connected with the flow of rivers or bodies of tidal water into the sea.

Bars.

In some instances, such, for example, as the Forth, the junction of the river with the sea occurs without giving rise to any very perceptible or marked phenomena; the one seems to glide naturally into and be mingled with the other, without producing any apparent disturbance of the currents or change on the bed of the channel. But such cases are exceptions; and, generally speaking, we may safely affirm that the junction of a river with the sea gives rise to what is termed a "bar,"—the most difficult subject with which the hydraulic engineer has to grapple, and the nature and cause of which we have now to discuss.

A bar, then, is the name applied to that shallow part of a channel which occurs at the junction of a river or estuary with the sea. On either side of it—that is, both seaward and landward of it—there may be ample depth of water for all purposes of navigation, but the bar forms the regulating navigable depth, and no passage over it can be obtained until the tide has risen sufficiently high to enable vessels to

cross it. The depth at low-water on the bars of some of our rivers is as follows:—

The Mersey has a depth of from	9	to	10	feet at low-water.
„ Tyne	6	to	7	do.
„ Wear	3	to	4	do.
„ Ribble	7	to	8	do.
„ Tay	16	to	18	do.

And while these limited depths exist on the bar, there is in all of these cases ample depth within, or landward, for vessels of the largest class to lie afloat at all times of tide.

Theories to account for formation of bars.

Many theories have been propounded to account for the phenomenon of the bar. Some have advocated the idea that bars are composed of materials held in suspension by the river, and deposited so soon as its current is checked by meeting the still water of the ocean. But this theory, at all events as regards sea bars, of which we are now treating, is disproved by the facts of the Dornoch Firth, to which we have already alluded. The bar at that place occurs at a point 14 miles seaward of the point at which the river enters the sea. The idea that a bar of such magnitude as that at the Dornoch Firth, could be formed by the detritus brought down by the small rivers Oykell and Cassily, is wholly untenable, and is indeed contradicted by the fact that the bar and adjoining banks are composed of pure sand; and hence the writer attributed its formation, when he examined the firth in 1842, entirely to the action of the sea. We find that Mr Ellet, though founding his opinion on totally different premises, also comes to the conclusion that the bars of the Mississippi were not due to materials deposited by the outgoing stream. In explaining his views, he writes as follows:—"The velocity of the river is not destroyed, nor very sensibly diminished, at the bars. When the river was rising, but still far from

being at full height, I measured the velocity of the current on the bar of the Pass à la Loutre, and found it to vary, at different times and places, from 3 feet to $3\frac{1}{2}$ feet per second, or from 2 miles to $2\frac{1}{10}$th miles per hour. I measured it also repeatedly on the south-west bar, and found it there 3 feet per second, or about 2 miles per hour. But there are many parts of the river where the speed of the current does not exceed $2\frac{1}{2}$ miles, or even 2 miles per hour, in times of flood, and where it is, notwithstanding, more than 100 feet deep. In fact, on testing the velocity of the south-west pass, 4 miles above the bar, and in 5 fathoms water, I found the current to be but 2 miles per hour,—precisely the same as it was under like circumstances of wind and tide on the bar. The current of the Mississippi sweeps over the bars at the mouths of the passes, and at periods of flood many miles out into the gulf, with a velocity almost undiminished by its contact with the waters of the gulf." He therefore concludes that there is in the Mississippi no retardation of the river's velocity on the bar to account for any deposit due to such a cause. Another theory attributes bars to the want of sufficient scouring power; but when we find bars existing at the mouths of such rivers as the Mississippi, we cannot attach much importance to such a suggestion. Another theory attributes the *absence* of a bar to "the presence of a nearly equal duration of the period of the ebb and flow in the lower reach of the river accompanied by an extremely gentle inclination of its surface at low water."[1] To refer again to the Dornoch Firth, we have an equal duration of the ebb and flow throughout the firth, and a surface practically level, and yet we have as perfect a specimen of a bar at

[1] *Treatise on the Improvement of the Navigation of Rivers*, by W. A. Brooks.

the Gizzen Briggs, at the mouth of the firth, as can possibly be imagined. We cannot, therefore, in endeavouring to account for the existence of bars, or the exemption from them, accept the explanations to which we have alluded.

The bars with which we have to do in this country may be said to be of two kinds; one class of bars is due to the hard formation of the bottom, which occurs in some situations; the other class is due to the action of certain elements, on the soft matters of which the bottom in other places is composed. Of the first class are such bars as that at Ballyshannon in Ireland, or at the entrance of Loch Fleet in Sutherlandshire, both of which the writer has had occasion professionally to examine. The bar at Loch Fleet, for example, is composed of boulder stones firmly imbedded in a mass of indurated gravel, and is obviously a continuation of a bed of similar formation which seems to traverse the coast at that place. The consequence is, that no scouring power can prove available in deepening the channel. Such bars being entirely due to the hardness of the bottom, are generally comparatively easily treated by the engineer, and an encouraging prospect is held out that their removal will be attended with permanent benefit, since, by excavating a channel through them, the engineer at the same time removes the evil and its cause.

In the other class are comprehended those sand-bars which occur at the mouths of the firths of Dornoch and Tay, and of the Tyne, Wear, Mersey, Ribble, and other tidal rivers and estuaries; and it is to the formation of these capricious and troublesome accumulations that the theories to which we have alluded apply. The true source of all such bars is to be found, as already stated, in the action of the sea. The natural effect of the sea is to throw up sand, and form a continuous line of beach across the mouths

of all our tidal rivers and inlets; while, again, the flow of the tidal and fresh-water currents tends to maintain an open channel through the beach. In this way the antagonistic action of the waves of the sea on the one hand, and the currents of the estuary or river on the other, produce the well-known feature of a submerged beach or sand-bank, extending from shore to shore across our inlets, having a deeper channel through them, which channel is termed the "bar." This explanation is due to the Abbot Castelli, who, in his work on the Mensuration of Running Waters, written in the beginning of the seventeenth century, gives the following clear announcement of his views:[1]—"As to the other point of the great stoppage of ports, I hold that all proceedeth from the violence of the sea, which being sometimes disturbed by winds, especially at the time of the waters flowing, doth continually raise from its bottom immense heaps of sand, carrying them by the tide and force of the waves into the lake; it not having on its part any strength of current that may raise and carry them away, they sink to the bottom, and so choke up the ports. And that this effect happeneth in this manner, we have most frequent experience thereof along the sea-coasts; and I have observed in Tuscany, on the Roman shores, and in the kingdom of Naples, that when a river falleth into the sea, there is always seen in the sea itself, at the place of the river's outlet, the resemblance, as it were, of a half-moon, or a great shelf of settled sand under water, much higher than the rest of the shore, and it is called in Tuscany *il cavallo*, and here, in Venice, *lo seanto;* the which cometh to be cut by the current of the river,

[1] *The Mensuration of Running Waters*, by Don Benedetto Castelli, Abbot of St Benedetto Aloysio, and professor of the mathematics to Pope Urban VIII. in Rome; translated by Thomas Salusbury, Esq., London, 1661.

one while on the right side, another while on the left, and sometimes in the midst, according as the wind fits. And a like effect I have observed in certain little rillets of water along the Lake of Bolsena, with no other difference save that of small and great.

"Now whoso well considereth this effect, plainly seeth that it proceeds from no other than from the contrariety of the stream of the river to the impetus of the sea-waves; seeing that great abundance of sand, which the sea continually throws upon the shore, cometh to be driven into the sea by the stream of the river, and in that place where these two impediments meet with equal force, the sand settleth under water, and thereupon is made that same shelf or *cavallo;* the which, if the river carry water, and that any considerable store of it shall be thereby cut and broken, one while in one place, and the other while in another, as hath been said, according as the wind blows; and through that channel it is that vessels fall down into the sea, and again make to the river, as into a port. But if the water of the river shall not be continual, or shall be weak, in that case the force of the sea wind shall drive such a quantity of sand into the mouth of the port and of the river as shall wholly choke it up. And hereupon there are seen along the sea-side very many lakes and meers which at certain times of the year abound with waters, and the lakes bear down that inclosure, and run into the sea.

"Now it is necessary to make the like reflections on our ports of Venice, Malamocco, Bandolo, and Chiozza, which in a certain sense are no other than creeks, mouths, and openings of the shore that parts the lake from the main sea; and therefore I hold that if the waters in the lake were plentiful, they would have strength to scour the mouths of the ports thoroughly and with great force; but

the water in the lake failing, the sea will, without any opposal, bring such a drift of sand into the ports, that if it doth not wholly choke them up, it shall render them at least unprofitable and impassible for barks and great vessels."

Conditions under which bars are formed.

The conditions under which such accumulations are formed the writer believes to be,—1*st*, The presence of sand or shingle, or other easily moved material; 2*d*, Water of a depth so limited as to admit of the waves during storms acting on the bottom; and 3*d*, Such an exposure as shall allow of waves being generated of sufficient size to operate on the submerged materials.

In confirmation of this opinion, we may once more refer to the Dornoch Firth. The Oykell, as has been shown in Section II., joins it at a point about a mile below Bonar Bridge, but we find no indication of what may be termed a bar throughout the whole of the sheltered part of the firth, which extends for 12 miles seaward of that point, until we reach the outer portion which is exposed to the unbroken sea of the Moray Firth, and there we find an extensive sand-bank, forming, as it were, a continuation of the shore on either side, and stretching quite across the mouth of the firth, with the bar in the centre of it. But the fact, that in all such bar-rivers and estuaries the depth is often found to be seriously diminished after heavy seas, is beyond doubt, and serves as a further confirmation of the correctness of the theory for which we are contending.

The same reasoning may explain why, in such a case as the Firth of Forth, for example, no bar exists. The Firth of Forth is an inlet or arm of the sea, of great width and depth, the seas entering it do not act on the bottom, so as to cause a heaping up of the material of which it is composed, in the same manner as in a shallow sea. This great natural depth continues as the Forth gradually contracts; and before

the necessary conditions for the formation of a bar occur—namely, sufficiently shallow water and presence of sand—the sea is so land-locked that waves of sufficient size to produce the necessary effect cannot be generated. There is, in fact, in the Forth that gradual diminution of depth, and increase of shelter, which combine to produce the phenomenon of a river without a bar.

We must also notice a cause for the formation of bars advanced by Mr Ellet. Although it is not applicable to the rivers in this country, still, from the observations he has made, we think it likely that his theory may be held to account for the bar of the Mississippi. It is founded on the fact, that at the junction of a river with the sea the fresh water flows in a stratum above, and distinct from, the salt water, for some distance after entering the ocean. This is occasioned by the higher specific gravity of salt water, the weight of fresh water being 1000, while that of salt is 1026.

Relative specific gravities of salt and fresh water.

Before noticing Mr Ellet's theory, however, we may state, that so far as we are aware, the first observations made on this subject were those instituted by the late Mr Robert Stevenson, of Edinburgh, on the River Dee in Aberdeenshire, in the summer of the year 1812, while engaged in surveying that river with reference to a disputed right of salmon-fishing. Mr Stevenson, in his report on that subject, states that, by means of an instrument devised for that purpose, he ascertained that the salt or tidal water of the ocean flowed up the channel of the River Dee, and also up Footdee and Torryburn, in a distinct stratum, next to the bottom and under the fresh water of the river, which, owing to the specific gravity being less, floated upon it, continuing perfectly fresh, and flowing in its usual course towards the sea, the only change discoverable being in its level, which was raised by the salt water forcing its way under it. The

Experiments at the Dee.

tidal water so forced up continued salt; and when the specific gravities of specimens from the bottom were tried, they were found to possess the greater degree of specific gravity due to salt water, while the surface specimens were found to be specifically unaltered.

Similar observations have been made by the writer of this article in several places, with the same results. The appearance of fresh water floating on the surface of the sea is no doubt familiar to most persons. It occurs at the mouths of many of our rivers, and is most apparent when they are in flood, from the brown tinge given to the water, which is easily discoverable for many miles at sea. It is well known on our coasts to the crews of the welled smacks employed in cod-fishing, who invariably lose a great portion of their live stock if they happen to encounter what they term "a fresh," which is believed by them to be a brackish portion of the sea, caused by the imperfect admixture of fresh water discharged from rivers in flood. On this subject the following passage from the work[1] of Father Manuel Rodriguez, a Spanish Jesuit, is interesting, and its correctness, as regards the extent to which the influence of large rivers is felt, has since been corroborated by the investigations of Colonel Sabine.[2] "This river," says Rodriguez, speaking of the Amazon, "is like a tree; its roots enter as far into the sea as into the land. It communicates to it a flavour, so that at 80 leagues within the sea its waters are seen, and taste sweet, and in a semicircle of 100 leagues in circumference they form a gulf not the least degree brackish, so that sailors call it the fresh sea."

[1] *El Maranam y Amazonas*, Madrid, 1684, p. 18.

[2] *An Account of Experiments to determine the Figure of the Earth, as well as on various other subjects of Philosophical Engineering*, by Edward Sabine, London, 1835, p. 445.

But to return to the Mississippi: Mr Ellet, in the following extract, says:—"The river water does not mix suddenly with the sea, but rises upon it, floats over it, and rushes far out into the gulf on the top of the dense sea water, by which it is buoyed up. I tested this repeatedly, and found uniformly a column of fresh water, nearly 7 feet deep, in the gulf, entirely outside of the land, and salt water at a depth of 8 feet from the surface, and extending thence to the bottom. The river does not come down with a certain normal depth and speed, and encounter the gulf at the bar. No such process takes place. There is no sudden destruction of velocity, or consequent deposit of suspended silt. But the water of the Mississippi does not move over the surface of the gulf at a speed of 3 feet per second without imparting a portion of its motion to the sea.[1] The fresh water and the salt water take the same direction towards the sea, and with nearly the same velocity, but yet keep separate. This state of things clearly cannot exist at the bottom; for as the river water is for ever coming forward, if the salt water all flowed towards the gulf, it would all be carried out, and river water would take its place. Salt water must come in from some quarter, to supply the current of sea water that is for ever setting towards the gulf, beneath the water discharged by the river. This salt water can only come from the sea, and can only come in along the bottom. It is, in fact, an eddy that is here at work, the movements being in a vertical instead of a horizontal plane. Now, the question is, How does this account for the existence of the bar? The fresh water running out cannot

[1] This is in harmony with Venturi's well-known experiments, from which he found, that a body of water in motion leads or drags with it the particles of water at rest with which it may be in contact.

produce deposit, for it has velocity enough to sweep away a foundation of coarse gravel. The outpouring salt water immediately beneath the fresh, cannot produce deposit, because it also has a velocity seaward strong enough to remove anything that is brought down the Mississippi. The salt water that is coming in might produce, and I doubt not does produce, a deposit, for it passes over the soft muddy bottom of the gulf, and moves into the river, and along the bar, at a very slow rate. According to these facts, and this reasoning, there must be usually on the bar three distinct strata: 1*st*, Fresh water, running out at top, found by experiment on the S.W. bar to have a velocity of 3 feet per second. 2*d*, Salt water below the fresh, also running out with nearly the same velocity as at top; and 3*d*, Salt water coming in slowly along the bottom, and apparently a sheet of salt water between that running out and that coming in, which will be without motion.

"But as already said, and as is obvious, all the sea water that comes in must go out again. It comes in along the bottom, and it must go out between the column of salt water coming in and that of the fresh water going out. Each particle of salt water, therefore, must change its direction and position in elevation. It must pass from an inward-bound lower stratum to an outward-bound upper stratum. But in passing through this change of motion, its velocity up stream must be neutralized. It passes, to use a technical term, the *dead point*. At this point it may cease to bear its whole burden of mud, which it has brought from the gulf further forward. It leaves it, or a portion of it, at the turning-point. This turning-point is the place where the bar for the time being is in process of formation. But as the upper and lower strata are moving in opposite directions, the intermediate column must of necessity have a

rotatory motion; that motion must be shared by the lower column of salt water, and this turning-point must therefore be found at the same time at different places along the bar."

Mr Ellet gives an interesting detail of his experiments on the saltness and freshness of the water, as taken from different depths, and also of the means he took to ascertain the strength and directions of the two under-currents referred to in his ingenious theory of the formation of the bar; but the details are too long to give in this sketch of his researches.

We have seen that bars, in some situations, are formed by the hard strata of which the bottom is composed; that in other places they are due to the waves of the sea; and that in the case of the Mississippi Mr Ellet attributes the phenomenon entirely to the eddy caused by an under-current inwards.

The removal of *hard bars* is, as already noticed, likely in most cases to result in a successful issue; but the treatment of those bars which are due to the waves of the sea, with which class of phenomena we have chiefly to do in this country, is an operation not only more difficult to deal with, but far more uncertain in its results.

Depth of water due to amount of back-water.

From what has been said, the reader will see that we believe the depth of water, on such bars as are caused by the waves of the sea, to be in some degree proportional to the scour produced by the tidal currents, which cross them four times in every twenty-four hours. If this assumption be correct, it is obvious that the principle which should guide us in all our considerations as to increasing, or even maintaining the depth upon sea-bars, is the preservation of a sufficient amount of tidal water to counteract the tendency of the sea to heap up detritus at the mouths of our harbours,

These two agents, the *waves* and the *tidal scour*, are constantly opposed the one to the other: a storm from the sea, or a heavy flood from the land, occasionally causes the one or the other to have the ascendancy; but this is only temporary. A variation in the depth of water on the bars of our harbours, caused by such temporary disturbances, may occasionally occur; but nevertheless, unless some work of magnitude is formed, so as to alter permanently the natural disposition of matters, no pilot has any difficulty in fairly estimating what is the general navigable depth over the bar of any of our seaports.

Comparison of amount of river and tidal water in firths and estuaries.

That the beds of the upper parts of rivers are scoured, and their depth maintained by the flow of the fresh-water stream, is not to be questioned; and it is also beyond doubt, that in many situations the upper portions of the tidal compartments of rivers are kept open in a great measure by the fresh-water stream; but it is no less certain that the opinions which would assign the depth of water in the lower parts of tidal rivers, and also through estuaries and across bars, to any other cause than the action of tidal water as the chief agent, are erroneous. We think this will be apparent by a reference to some of the investigations which have from time to time been made to ascertain the amount of the river or fresh water, as compared to the volume of the tidal water of some of our firths and estuaries.

Cromarty Firth and River Conon.

By means of a series of careful observations and measurements made at the Cromarty Firth in 1837, to which reference has already been made, Mr Alan Stevenson found that the River Conon, when highly flooded (a state of matters which of course occurs only occasionally), discharges during twelve hours a quantity which is only equal to $\frac{1}{57}$th part of the water which passes out of the firth at every ordinary spring tide, and $\frac{1}{73}$th of that which passes

out at neap tides. In its summer-water state, the produce of the river is reduced to $\frac{1}{1644}$ of the discharge of the firth in spring, and $\frac{1}{760}$ of the discharge in neap tides; a quantity too small to affect appreciably either the velocity of the currents of the firth or their scouring power. It has often been argued, that in situations where the velocity of the ebb exceeds that of the flood tide, the excess is due to the increased quantity of water passing out with the ebb, the volume of the ebbing waters being assumed to be augmented by the amount discharged by the river. But this is wholly disproved in the case of the Cromarty Firth; for while the increased quantity due to the river is seen to be only from $\frac{1}{760}$ to $\frac{1}{1644}$, the average velocity of the flood tide at that place was found to be 2·9 miles per hour, while that of the ebb was 3·6; an increase which is in all probability due to the tide beyond the Suters falling more rapidly than it rises, and thus producing a greater head and more rapid current on the ebb, but is assuredly not due to any augmentation of water from the discharge of the Conon.

The Tay presents another example of the disproportion between the tidal and river waters. That river, as gauged by Mr Leslie when in flood, was found, including the Earn, to discharge 969,340 cubic feet per minute. Mr Walker, in his report to the trustees of Dundee harbour, assumes the discharge in round numbers at one million cubic feet per minute, or 240,000,000 during four hours, and arrives at the following conclusion:—"To compare the above with the effect of the tidal water at Dundee, I assume 15,000 acres as the average area (above Dundee) of the reservoir or estuary during the first four hours of the ebbing tide, and the vertical fall of tide during these four hours to be 11 feet. This will give 7,187,400,000 cubic feet, or thirty times the 240 millions of river water. To compare the

The Tay.

effect upon the *bar*, the area of the river between Dundee and the bar must be added; and the tidal water upon the bar will then be upwards of *forty times* the river water."

Works recommended favourable for bars.

It will be apparent that an important question is suggested as to the manner in which such works as we have recommended for improving the upper parts of rivers may operate in assisting or retarding the scour of the bar. We have no hesitation in replying, that if executed in the manner we have indicated, they will improve the higher part of the river without prejudicially affecting the bar, and in certain cases they will operate beneficially on the bar also.

Piers for entrance to rivers.

The construction of piers for improving the entrances of rivers, as in the case, for example, of the Wear at Sunderland, is more properly included in the subject of harbours. Such works seem to us to act beneficially, not so much by increasing the *depth* on the bar, as by limiting the extent of shoal water at the entrance to the river. In its natural state such a river as the Wear flows across the beach from high to low water in a broad and shallow channel, the direction of which is ever changing. It thus forms a long bar or shoal, with broken water throughout its whole extent. But the projection of piers across the beach affords shelter from the waves, and admits of a navigable channel being excavated and maintained; and after a vessel crosses the short bar, which occurs at or near the pierheads, she not only gets into deeper water, but has the additional advantage arising from the shelter afforded by the piers. To this extent piers in such situations are highly advantageous. They further act beneficially in directing the flow of the tidal currents in a fixed channel across the beach and bar, and, in connection with an increase of tidal capacity in the interior, such as we have mentioned as the result of the works on some rivers, they cannot fail, if judiciously designed, to operate bene-

ficially by maintaining an increased depth of water on the bar.

In certain situations where the coasts are faced with gravel or shingle beaches, accumulations or bars may be lessened by means of groynes, so formed as to intercept the gravel, and either retain it, or lead it past the harbour's mouth into an adjoining bay. The writer has in several situations recommended the adoption of such works; and Mr Walker has applied them with success at the harbour of Newhaven in Kent, where, in conjunction with increased backwater, due to dredging and removal of obstructions, the depth on the bar has been materially increased. Groynes.

SECTION IX.

FORMATION AND RECLAMATION OF LAND.

Schemes for gaining land and improving navigation not generally compatible.

Such twofold schemes as have for their ostensible object the improvement of rivers and the *formation of land*, have generally been unsuccessful in benefiting navigation. We do not affirm that river-works, constructed on the principle which we have advocated, have not the effect of *making land*, in the particular sense in which we shall afterwards explain it; but we do state that *land-making* is no part of sound *river engineering*. Judiciously designed works may, as we shall presently explain, have the effect of reclaiming and protecting land, while at the same time they, as their primary object, benefit navigation; but we know of no case where the interests of navigation have been promoted by any measure which has for its object the conversion of large tracts of tide-covered sands into cultivated fields.

River Dee.

We refer to the Dee in Cheshire, as an aggravated instance of the incompatibility of the two interests.[1] The outline of this river is shown in Plate I., from a survey by Messrs Stevenson, made in 1838. The River Dee Company, incorporated by act of Parliament in 1732, have from time to time reclaimed from the upper part of the estuary a large tract of land, extending to about 4000 acres, which is now in full cultivation; and alongside of this gradually

[1] *Great Britain Coasting Pilot*, by Captain Greenville Collins, hydrographer in ordinary to the King's most excellent Majesty London, 1767; *Reports to the Admiralty*, by Captain Washington; *Report of Tidal Harbour Commissioners*; *Report* by Messrs Stevenson, 1839.

gained territory the river has been conducted from Chester to near Flint, in a narrow canal of about 8 miles in length, and 400 feet in width. A considerable portion of land has also been reclaimed on the Flintshire side of the estuary, though not by the proprietors of the Dee Company; and it is believed that the aggregate amount which has from first to last been gained from the sea is about 7000 acres. Now it is well authenticated, that previous to the commencement of the land-making operations on that river, there was a depth of not less than a fathom at low water of spring tides up as far as Burtonhead, and that there was an anchorage for vessels of the largest size opposite to Parkgate, the positions of which places are marked on the plan. But when the writer surveyed the Dee in 1838, the depth of 6 feet was not found for more than 6 miles below Burtonhead, the low-water features of the estuary having been forced to that extent further seawards by the extensive reclamation of land in the upper part of the estuary, and the consequent diminution of the tidal scour. It cannot, we think, be disputed, that the effect of the works executed on the River Dee, whatever may have been the anticipations of their projectors, has been to shut out the sea, and form land at the expense of the navigation. They are designed, in fact, in direct opposition to the general principle laid down in the present treatise, which provides for the admission of the greatest possible quantity of tidal water.

Increase of tidal water produced by works on the Tay and Lune.

It seems also equally clear that an increase of tidal water must inevitably attend the execution of such works as we have proposed; but in proof of this assumption, and in contrast to the case of the Dee, it may be well for the reader's information to cite examples which have occurred in practice. Proceeding on actual calculations of comparative sections of the River Tay before and after the operations, the writer

found that by the lowering of the low-water line, consequent on the improved state of the river, an additional quantity of sea water, amounting on an average to not less than 1,000,000 cubic yards, or 760,560 tons, is *during every tide* propelled into and again withdrawn from that part of the river which lies above Newburgh. This quantity is equal to two hours' discharge of the Tay in its ordinary state; and it therefore follows that the additional tidal discharge for one year is equal to two months' constant ordinary flow of the River Tay. In the same way it was found by calculation that the additional amount of tidal water admitted every tide into the Lune above Heaton, in consequence of the operations, was 736,278 cubic yards.[1] To estimate truly the beneficial effects of these important changes on the scouring power of the Tay and the Lune, it must be kept in view, that in both cases the increased volume of tidal water, being obtained by the enlargement of the *low-water channel*, operates during *every tide*, and thus may be held to produce the *maximum* amount of benefit; for it is obvious that a cubic yard of low-water space, gained in the low-water channel, and filled by every tide, is very much more valuable than a similar amount of space gained at or near high-water of spring tides, which is filled only at remote intervals.

Depression of low-water line apt to mislead.

The tendency, then, of the whole system of works recommended in this treatise is to lower the low-water line, and to admit an increased amount of tidal water to act on

[1] The mere cubic contents dredged from a ford or shoal often form no measure of the gain of tidal water due to the operations, because the removal of such an obstruction has the effect of lowering the low-water line for a considerable distance up the river, the extent to which the influence of the works extends depending on the amount of fall; and the whole of the wedge-shaped space included between the old and new low-water lines is a clear gain of tide-water, and the cubic contents of this space generally greatly exceed the cubic quantity of materials removed from the ford by dredging.

the low-water channel. But the depression of the low-water line, particularly when the river is confined by walls in the lower part of an estuary, conveys the impression that a great rise has taken place in the level of the adjoining sand-banks, and it has consequently been thought that the erection of river walls is inconsistent with the principles of non-exclusion of tide-water which we have recommended; but we are enabled to show that this is not the case. In its natural state, the channel of such an estuary as the Lune or the Ribble, as already explained in section iv., is subject to constant change of position. The writer has seen many acres of marsh or grass land in such estuaries carried off by the waves, and the solid matter of which they were composed scattered over the shores and sand-banks. Now, the effect of fixing the channel by means of walls, in the manner which has been recommended, is to form one permanent navigable track; and the banks on either side, being no longer subject to the periodical inroads of the river or tides, gradually rise in elevation until they are capable of producing vegetation, and ultimately become what are termed marsh lands. When a river channel has been thus fixed and confined by walls, it has been ascertained by repeated observation that the tidal water comes up the channel in a comparatively pure state, instead of being loaded with particles abraded from the sand-banks and marshes. It has also been found that the process of deposit at the sides of an estuary so improved goes on very slowly after it has reached a certain stage; for the materials deposited on the upper parts of the banks are, as afterwards more particularly described, exceedingly fine, and are carried only by the highest tides, which seldom reach those elevated portions of the shores. From all these considerations we infer that the effect of river-walls upon an estuary is to prevent the

constant disturbance of the materials of which the banks are composed, but not to occasion additional accumulations.

As tested in the Lune.

The writer had an opportunity, in the case of the Lune, of testing by actual measurement in how far the raising of the banks, caused by the erection of walls, was due merely to a new disposition of the materials which originally filled the bed of the estuary, or to additional foreign matters deposited in consequence of the operations; and the following results are instructive, being, it is believed, the only observations that have been made to determine the state of the sand-banks of an estuary after the river has been improved, as compared with their former condition.

The rubble walls and other works constructed on the Lune caused, as might have been expected, a very considerable alteration in the position and form of the sand-banks in the estuary; and this alteration, in connection with the depression of from 2 to 3 feet in the low-water level of the river, was apt to lead a casual observer to suppose that a great accumulation of sand had taken place, and consequently that a corresponding amount of back-water had been excluded. The writer was authorized by the Admiralty to make such observations as were necessary to determine the true state of the case. Figure 24 represents the changes that were produced by the works. Over the whole area which is represented as covered by sand a deposit had taken place, the banks being higher than formerly; whereas the whole area included in hatched lines had been scoured, the banks having been lowered. A careful calculation was made, founded on numerous sections taken in 1838, before the works commenced, and in 1851, after their completion. The result of this investigation was, that after the completion of the works, the amount of deposit on the space shown as sand in the cut

River Lune.

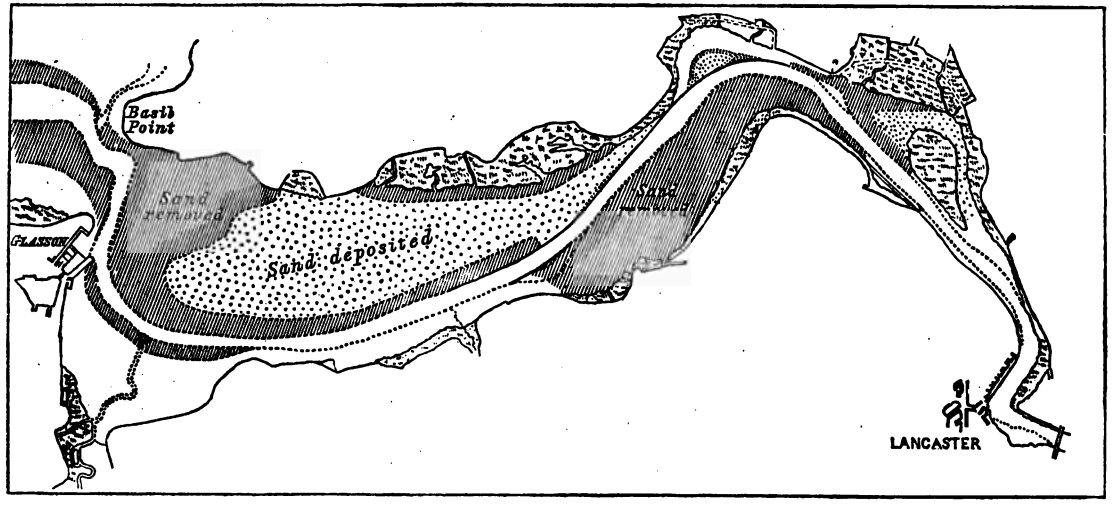


Fig. 24.

was 3,070,146 cubic yards; while the amount of scour on the space shown by hatched lines was 2,810,449 cubic yards; giving an excess of deposit of 259,697 cubic yards. But the amount stated as having been scoured does not include what has been taken away below Glasson and Basil points; and which has doubtless been deposited in the bank above. The survey of 1838 did not afford data for ascertaining the amount of what had been scoured from below Glasson with sufficient accuracy to admit of its being included in the foregoing calculations. But an amount of scouring was ascertained to have actually occurred at that place, which was amply sufficient to counterbalance the surplus of 259,697 cubic yards of deposit, as given in the above statement.

Such a result, we think, may indeed be expected; for it is difficult to conceive in what way parallel walls formed in an estuary can operate either in bringing down additional alluvial matters from the river above, or in bringing up additional detritus from without the bar.

Holding these views, and supported by the actual observations made in the case of the Lune, we therefore conclude—1*st*, That works executed in accordance with the principles laid down do not necessarily produce additional accumulation of matter, but *simply alter the disposition of the existing materials of which the bed of the estuary was originally composed.* 2*d*, By deepening the navigable track they admit of a large accession of water to act upon the low-water channel during all tides, and at the most favourable period of the tide. 3*d*, That the depth of water on such bars as are produced by the action of the waves may be maintained, and even increased, by means of the works which have been described as applicable to the intermediate or tidal compartments of rivers.

While treating of deposits, this is probably the proper

Size of particles transported proportional to velocity of stream.

place to observe, that the size of detrital particles which can be carried by a current depends on the velocity of the stream, the nature of the bottom along which the detritus is moved, as well as the shape of the particles of which the detritus itself is composed, and is altogether a subject so dependent on special circumstances, that there is great difficulty in laying down rules which can be generally applicable. The following are the results of experiments made by Bossut, Dubuat, and others, on the size of detrital particles which streams flowing with different velocities are said to be capable of carrying :—

3 in.	per sec.	=0·170	mile per hour will just begin to work on fine clay.
6 „	„	=0·340	do., will lift fine sand.
8 „	„	=0·4545	do., will lift sand as coarse as linseed.
12 „	„	=0·6819	do., will sweep along fine gravel.
24 „	„	=1·3638	do., will roll along rounded pebbles 1 inch in diameter.
3 ft.	„	=2·045	do., will sweep along slippery angular stones of the size of an egg.

The only recent experiments made on this subject are those of Mr T. Login, C.E., given in the *Proceedings of the Royal Society of Edinburgh*, vol. iii., p. 475, which were made with a stream seldom exceeding half an inch in depth; and are as follows :—

Nature of Materials.	Rate of sinking in water.	Current required to move.	
	Feet per minute.	Feet per minute.	Mile per hour.
Brick-clay when mixed with water, and allowed to settle for half an hour	·566	15	·170
Fresh-water sand	10	40	·454
Sea sand	11·707	66·22	·752
Rounded pebbles about the size of peas	60	120	1·37
Vegetable soil	...	50	·56

Brick-clay in its natural state was not moved by a current of 128 feet per minute, or 1·45 mile per hour.

We give these results as they have been stated by their authors; at the same time it is necessary to say that, for the reason above mentioned, we consider their application in practice to be very uncertain. Regarding the subject in a general point of view, however, certain laws as to the transmission and deposition of detritus will be found applicable to certain situations. On this subject Sir H. De la Beche says:[1]—"Where the velocity of a river is sufficient to produce attrition of the substances which it has either torn up, collected by undermining its banks, or which have fallen into it, they gradually become more easy of transport, and would, if the force of the current continued always the same, be forced forward until the river delivered itself into the sea; but as the velocity of a current greatly depends on the fall of the river, the transport is regulated by the inclination of the river's bed. Now it is well known that this inclination varies materially even in the same river; so that it may be able to carry detritus to one situation, but may be unable to transport it further under ordinary circumstances, in consequence of diminished velocity. As a general fact, it may be fairly stated that rivers, where their courses are short and rapid, bear down pebbles to the seas near them, as in the case of the Maritime Alps, &c.; but that where their courses are long, and change from rapid to slow, they deposit the pebbles where the force of the stream diminishes, and finally transport mere sand or mud to their mouths, as is the case with the Rhone, Po, Danube, Ganges, &c."

In rivers, lightest matters found next the sea.

This holds true in the case of such rivers as those to which Sir H. De la Beche refers; but it will be found that the case is exactly reversed in tidal estuaries. There the heavier sands and deposits are found at the mouth of the estuary, and the particles are lighter as we recede inwards. The writer has tested this on several occasions, more particu-

The reverse of this the case in tidal estuaries.

[1] De la Beche's *Geological Manual.*

larly in the Dee, the Ribble, the Lune, the Wear, the Forth, and the Tay, by agitating equal quantities of sand and deposit (taken from different parts of the tidal estuary) in equal quantities of water, and observing the time which elapsed in each case before the materials were deposited and the water assumed a state of purity. The result of these observations proved that the sand of outer or seaward banks was composed of large particles, which were held in suspension only a few seconds, and that in the inner parts of the estuary the deposit decreased in weight, and that *generally* it decreased from low to high water, where the silt was exceedingly fine, and remained in suspension in some cases even for hours after the agitation of the water. The following statement by Mr William Bald of experiments made on materials taken from different parts of the bed of the Clyde, shows the variety of materials found in the same stream, and is a valuable record of the weight of the deposits which form the beds of our tidal rivers:[1]—

Deposits.	Lbs. to cubic feet.	No. of cubic ft. to the Ton.
Fine sand and a few pebbles laid in the box, loose, not pressed, nearly dry	87	26
Do. do. pressed	92	24
Mud at White Inch, dry, and firmly packed; contained very fine sand and mica	97	23
Wet mud, rather compact and firm, well pressed into the box	115	19
Wet, fine sharp gravel, well pressed	124	18
Wet running mud	122½	18·1
Sharp dry sand deposit in harbour	92	24·3
Port-Glasgow Bank (sand) wet, pressed into a box	120½	18·6
Sand opposite Erskine House, wet, pressed	116	19·3
Alluvial earth, pressed	93	24
„ „ loose	67	33

The writer of this article found the gravel of the Tay to be 18 feet to the ton.

[1] *Trans. of Institution of Civil Engineers*, vol. v., p. 330.

Quantity of matters in suspension.

The quantity of solid matter carried or held in suspension by rivers has also been made the subject of observation; but the different observers whose remarks have come under our notice have stated their results in different ways, some giving the *weight* and others the *bulk* of detritus. But assuming 18 cubic feet of solid matter to weigh a ton, we think the following table presents a fair view of the cubic measure of solid matter, and the ratios of volume and weight in each case. In submitting this table, we must observe that the discrepancies in the statements are so great, that further observations are necessary before any satisfactory conclusion can be arrived at; but we give the results as they have been stated by their respective authorities:—

Name of River.	Cubic inches of solid matter in every cubic yard of water.	Ratios of volume of solid matter to volume of water.	Ratios of weight of solid matter to weight of water.
Mississippi, mean...	15·5	$\frac{1}{3600}$	$\frac{1}{1331}$
Irrawaddy, in flood..	11·71	$\frac{1}{4926}$	$\frac{1}{1760}$
Do., ordinary state	4·1	$\frac{1}{14076}$	$\frac{1}{5027}$
Rhine, in flood	1·87	$\frac{1}{30854}$	$\frac{1}{11020}$
Do., ordinary state	1·13	$\frac{1}{51062}$	$\frac{1}{18236}$
Do., mean	1·5	$\frac{1}{38475}$	$\frac{1}{13741}$
Mersey, flood-tide...	29·	$\frac{1}{1986}$	$\frac{1}{709}$ salt water
Do., ebb-tide.....	33·	$\frac{1}{1745}$	$\frac{1}{623}$ salt water

From this table it will be seen that the Rhine, as compared to the others, is exceedingly pure; while the waters of the Mersey, on the other hand, hold in suspension a very large amount. It must be kept in view, however, that the source from whence the sedimentary matter in the Mersey is derived is very different from any of the other cases mentioned in the table. The main part of the solid matter in suspension in the Mersey, and indeed in all our tidal rivers, is sand, stirred up by the flowing tide, which is deposited again during the ebb-tide. The sedimentary matters in

such rivers as the Mississippi or the Irrawaddy, on the other hand, are borne down from the low tracts of alluvial country through which it flows, and form a constant and consequently increasing deposit at the mouth of the river.[1]

In all cases where the tidal currents across the mouths of such rivers are languid or altogether absent, as in the Mississippi, the Nile, the Danube, and other continental rivers, the deposits brought down are not carried away, but form deltas, which collect with greater or less rapidity in proportion to the quantity of material brought down and the depth of water in which it is deposited. Mr Ellet computes the delta of the Mississippi at 40,000 square miles in ex- Formation of deltas.

[1] Mr Ellet says that the sedimentary matter transported by the Mississippi forms $\frac{1}{3000}$th part of the *volume* discharged by the river. (Ellet, *On the Ohio and Mississippi.*)—Mr T. Login, C.E., in Pegu, states in a paper on the Delta of the Irrawaddy, read before the Royal Society of Edinburgh, session 1857, that the waters of the Irrawaddy contained $\frac{1}{11000}$th part of their *weight* of sediment during floods, and $\frac{1}{3333}$th part of their *weight* when the river was in a low state, and gives the mean deposit at 8 inches per cubic yard. —Mr Leonard Horner found that the water of the Rhine at Bonn contained from $\frac{1}{1331000}$th part of its weight during floods to $\frac{1}{3031}$th part of its weight in a low state. (*Arcana of Science and Art*, 1835.)—Captain Denham found that the tidal water of the Mersey contained 29 cubic inches of solid matter in every cubic yard during flood-tide, and 33 cubic inches in every cubic yard during ebb-tide. (*Observations on the Mersey*, by Captain H. M. Denham, R.N., Liverpool, 1840.)—Mr Lyell says:—"Hartsaeker computed the Rhine to contain, when most flooded, 1 part in 100 of mud in suspension. By several observations of Sir George Staunton, it appeared that the water of the Yellow River in China contained earthy matter in the proportion of 1 to 200. Manfredi, the celebrated Italian hydrographer, conceived the average proportion of sediment in all running water to be $\frac{1}{1000}$th. Some writers, on the contrary, as De Maillet, have declared the most turbid waters to contain far less sediment than any of the above estimates would import; and there is so much contradiction and inconsistency in the facts and speculations hitherto promulgated on the subject, that we must wait for additional experiments before we can form any opinion on the subject." (*Principles of Geology*, by Charles Lyell, F.R.S., London, 1830, vol. i., p. 247.)

tent, its average length from north to south being 500 miles. Assuming the sedimentary matter brought down at $\frac{1}{5000}$th of the volume of water, and the discharge of the river at 21,000,000,000,000 cubic feet per annum, he estimates that this vast accretion of deposited stuff must have formed at an average rate of 1 mile in 99 years, giving a period for its entire formation of something like 45,000 years! Sir H. De la Beche has, however, with reason, suggested that deltas would increase most rapidly at the first period of their formation, on account of the greater declivity of the river, and the supposition that the detritus from the interior would become gradually less, from the equalization of levels and the fewer asperities that agents have to act on; and thus it seems impossible to calculate from the present rate of accretion the time which the whole mass has taken to accumulate.

Adjoining property benefited by river improvements.

In concluding this treatise, we have to point out in what way, and to what extent, river improvements conducted on the principles advocated benefit adjoining property; for it is obviously highly important if the two objects of *river* and *land* improvement can be carried on simultaneously, and we think that to a certain extent this is perfectly practicable. The attempts of proprietors to protect the foreshores of their lands from the encroachments of rivers in tidal estuaries are often attended with great expense; and if those efforts prove for some time effectual in warding off the approach of the channel, the land speedily takes on vegetation, and is fit for pasturage. But the tenure by which such property is held is very slight; and the spot which today affords grazing for cattle may in a few tides become the navigable channel of the river. Now, it is obvious that the perfect protection from such encroachments afforded by the training and guiding of the low-water channel by longitudinal walls, adds materially to the value of the adjoining

property; for not only is the land beyond high-water mark completely protected from encroachment, but the marsh lands bordering the estuary become in fact *permanent property*, and not an ever-changing benefit held for one year and probably lost the next. Marsh lands so protected from waste are still, it is true, liable to be flooded by high tides, a circumstance, however, which is considered by some persons not injurious, but rather beneficial, for marsh pasture lands.

Level of vegetation on marsh lands.

The process of reclamation in all such cases goes on very slowly after it has reached a certain stage, because, as the banks rise, they are more seldom covered by the tide, and the materials deposited on the inner and higher parts of the banks are, as already stated, exceedingly fine, and are carried only by the highest tides, which seldom reach them. Mr Park has found on the Ribble that the first indications of vegetation appear when the banks are elevated 12 feet above the ordnance datum-line, which is the mean level of the sea. This height corresponds at the Ribble to about the level of high-water of neap tides. Mr Gordon[1] also found, that in the Norfolk estuary "the samphire began to settle on the sands, which the neap tides just cover," and that "grass began to grow about one foot above the samphire level." Such marsh lands, if left unprotected, must remain for ever liable to be covered during high floods or tides, and therefore cannot be said to be available as arable lands, without the erection of considerable works for the purpose of protecting them from floods, and providing for their effectual drainage. As the erection of such works, however, forms no part of river improvement, we allude to them in this place only for the purpose of remarking, that in all cases they should be erected with caution. There are situations in which the erec-

[1] *Report on Norfolk Estuary*, by L. D. B. Gordon, C.E., Glasgow, 1856.

tion of embankments for protecting land may be injurious to the interests of navigation; there are others in which such works, if judiciously laid out, may be harmless; but their effect in any case can only be determined by a careful consideration of the special circumstances of the locality in which they are erected. We know many cases where the interests of navigation have been sacrificed by unwarrantable encroachment; and, on the other hand, instances are not wanting where even important works have been embarrassed and crippled by an over-cautious regard to the principle of *non-encroachment* on the high-water line.

With reference more particularly to the operations of landowners, it is notorious that in many cases attempts to reclaim or protect property have led to serious and costly legal proceedings between landowners and the local conservators of navigations; and this we are sensible has in some instances arisen from a feeling, on the part of the landowners, that their operations could not be regarded as prejudicial. The local conservators, on the other hand, have generally no means of knowing what the ultimate intentions of the landowners are until their operations have proceeded so far as to render it impossible, if the interest of navigation require it, to stop or to remove the works without considerable loss. A difference of opinion has thus been raised, which has too often ended in an expensive lawsuit. We have long held the opinion that it would in many, if not in all, of our estuaries, be most desirable to have a line of conservation marked out by the Admiralty (without whose authority no encroachment can be made within high-water mark) for the regulation of all works for the protection of land. Were such a line defined, the landowners could then with confidence, and without risk of challenge, enter on such works within the line of conservation as they

considered necessary for the protection of their property, and a source of much difference of opinion and expensive litigation would be at once removed. We had hoped that the Tidal Harbour Commission, who have been enabled, through the exertions of Captain Washington, the hydrographer of the Admiralty, who was one of the commission, to give in their printed reports so valuable a fund of information on our tidal harbours, would have terminated their labours by pointing out and recommending some such system as we have suggested of defining lines of conservation for all the important rivers and estuaries of the country. It is obvious, however, that were such a duty to be performed, it must be committed to a duly qualified commission, acting most naturally under the Admiralty, and so composed that the protection of navigation, and the interests of landowners or trustees for public works, should be fully represented, the whole of its members being actuated by one common desire to do what is best for the community at large.

Note relative to Table.

Discharges of Rivers.

The quantities in the fourth column of the Table, in pages 153, 154, and 155, represent the discharges of the rivers in their ordinary state.

The following are the ratios between the discharges of certain rivers during low-water and when in flood; but it must be kept in view, as stated in treating of the formulæ for calculating the discharge, that its determination is a difficult problem; so that the results given in the table must be received with this caution as to their accuracy.

	Mean Discharge. Cubic ft. per min.	Flood.	
Clyde	48,000	194,000	1 to 4·0
Conon.....	7,969	216,589	1 „ 27·2
Erne.....	54,000	215,600	1 „ 3·9
Ganges.....	12,420,000	29,652,480	1 „ 2·4
Irrawaddy.....	4,500,000	45,000,000	1 „ 10·0
Mississippi.....	39,954,000	76,800,000	1 „ 1·9
Nile.....	1,386,000	13,200,000	1 „ 9·5
Tay.....	218,000	753,740	1 „ 3·4
Thames	80,220	475,000	1 „ 5·9

The high ratio on the Conon may be due to the steepness of its bed, and the absence of any natural lake or reservoir on its course to act as a regulator.

Physical Characteristics of Rivers.

Name of River.	Length in miles.	Area of drainage in square miles.	Ordinary discharge per minute in cubic feet.	No. of cubic feet discharged per square mile of drainage.	Slope of surface in inches per mile.	Part of River where slope occurs.	Length of River affected by tide, in miles.	Depth on bar at low water in feet.	Authority.
Amazon	4000	...	...	...	2·34	.....	400	...	N. Beardmore's Hyd. Tables.
Annan.....	35	...	...	...	66	Annan Waterfoot to Annan Bridge, 2 miles	2	...	Messrs Stevenson, C.E., Edin.
Boyne	60	700	180,000	257	...	.....	2	...	A. Nimmo, C.E.
Clyde	98	945	48,000	65	1½	Broomielaw to Port-Glasgow, 18 miles.....	22 above Port-Glasgow.	no bar	J. Ure, C.E., Glasgow.
Conon	35	399	7969	19·9	...	.....	...	...	Messrs Stevenson, Edin.
Coquet.....	44	...	...	...	60	.....	3½	...	E. K. Calver, R.N.
Dee, Aberdeen..	87	765	10,675	...	81	Lower part.....	...	...	J. Gibb.
Dee, Chester.....	85	620	...	...	11	Chester to Flint.....	32	East, West, 9 12	Messrs Stevenson, Edin. and Admiralty Report, by Captain Washington.
Forth.....	63	452	29,385	75·7	11	Black Dub to Stirling.....	15	no bar	Messrs Stevenson.
Before works were execut.	above Alloa.	...	...	...	13	Stirling to Alloa	above Alloa		
Foyle.....	55	1100	31,500	28·6	1·25	Londonderry to Culmore Pt.	23 above Londonderry.	...	Messrs Stevenson.
Ganges	1680	432,480	12,420,000	28·7	3·37	Rajmahal to Mirzapore Creek	...	...	Johnston's Physical Atlas. Beardmore's Tables. Rev. Mr Everest.
Irrawaddy	...	...	4,500,000	...	1·6 in summer ..... 3·8 in flood.....		105	...	T. Login, C.E.
Lune	50	...	...	...	26·76	Glasson to Heaton, 3¼ miles			
Before works were execut.	...	...	...	...	20·	Heaton to Lancaster, 2¼ ...	...	...	Messrs Stevenson.
					24·	Average slope between Glasson and Lancaster...			
Mersey.....	70	1,748	...	...	...	.....	...	9 to 10	Captain Denham, R.N.

Physical Characteristics of Rivers—Continued.

Name of River.	Length in miles.	Area of drainage in square miles.	Ordinary discharge per minute in cubic feet.	No. of cubic feet discharged per square mile of drainage.	Slope of surface in inches per mile.	Part of River where slope occurs.	Length of River affected by tide, in miles.	Depth on bar at low water in feet.	Authority.
Mississippi...	4400 includ. Missouri	1,226,600	39,954,000	32·5	2·8 3·25	ordinary { from Ohio to Gulf flood ..... { of Mexico	...	...	C. Ellet.
Ness.....	7	700	...	...	96	Loch Dochfour to Kessock..	2	...	Messrs Stevenson.
Nile.....	2240	520,200	1,386,000	2·6	5·5 3·25	when high { Cairo to Mediterranean... when low.. {	...	...	{ N. Beardmore. { Johnston's Physical Atlas.
Nith	45	...	...	...	20	Dumfries to Burron Point...	...	...	Messrs Stevenson.
Rhine	700	88,853	3,960,000	44·5	2119 119 63 20·7 7·7	Source to Reichenau..... Reichenau to Constance ... Constance to Basle ..... Basle to Cologne ..... Cologne to sea	...	...	{ Johnston's Physical Atlas. Beardmore's Tables. Falls and Discharge, from L. Horner, Esq.
Rhone	560	38,329	...	...	24·18	Besançon to Mediterranean	...	...	{ Johnston's Physical Atlas. Beardmore's Tables.
Ribble, before works.....	80	880	139,935	159	47·8	Lower 22½ miles	22½	5½	P. Park, C.E. Preston.
Severn.....	180	8,580	...	...	4·5 2 3 2 0·75 5 10·5 7·5 15 20·5 23·25 7	Diglis Weir to Upton Bridge Upton Bridge to Mythe Br. Mythe Bridge to Haw Br. Haw Bridge to Stonebench Stonebench to Rosemary Pt. Rosemary Pt. to Framilode Framilode to Newnham ... Newnham to Awre Point... Awre Point to Sharpness... Sharpness to Guscar..... Guscar to Inward Point ... Inward Pt. to Aust Head...	68	...	{ Remarks on the Tidal Phenomena of the River Severn, by Capt. F. W. Beechey, R.N.

Physical Characteristics of Rivers—Continued.

Name of River.	Length in miles.	Area of drainage in square miles.	Ordinary discharge per minute in cubic feet.	No. of cubic feet discharged per square mile of drainage.	Slope of surface in inches per mile.	Part of River where slope occurs.	Length of River affected by tide, in miles.	Depth on bar at low water in feet.	Authority.
Tay. before works.....	160	2,283	274,000	120	1·95 9·35 5·06	Flisk to Balmbreich..... Balmbreich to Newburgh Newburgh to Perth	35	18	Messrs Stevenson.
Tees.....	100	680	...	...	...	.....	22	6	John Murray, C.E.
Thames	204½ navigab.	5,000	102,000	20·4	20 ·92	Lechdale to Teddington ... Teddington to Yanlet Creek	66 from Nore.	no bar	Messrs Rennie, C.E.
Tweed.....	100	1,870	...	...	109 116 49	Confluence of Gala Water to Leader Water ..... Leader to Kelso..... Kelso to sea	..	...	A. Peterman, F.G.S.
Tyne.....	80	1,100	...	...	...	.....	18	6	E. K. Calver, R.N.
Wear.....	58	437	9500	22	16	New Bridge to sea.....	10	2 to 4½	Thos. Meik, C.E., Sunderland.

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